Management of Volunteer Glyphosate-resistant Canola (*Brassica napus* L.) in Glyphosate-resistant Soybean (*Glycine max* L.) Crops

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ABSTRACT

In recent years, soybean acreage has increased significantly in western Canada. One of the challenges associated with growing soybean in western Canada is the control of volunteer glyphosate resistant (GR) canola, as the majority of soybean cultivars are also glyphosate resistant. The objectives of this thesis were (1) to determine the most effective combination of pre- and post-emergence herbicides to control volunteer GR canola in GR soybean; and (2) to determine the optimal soybean seeding rate and seeding date for soybean in western Canada to compete with volunteer canola, while still being economically feasible for producers. Experiments were conducted in 2014 and 2015 at three sites in Saskatchewan and one site in Manitoba. In the herbicide study, treatments consisted of combinations of one of three different pre-emergence herbicide treatments (2,4-D, tribenuron and saflufenacil) and five different post-emergence treatments (bentazon, imazamox+bentazon, cloransulam, thifensulfuron and fomesafen), as well as a glyphosate-only check. Treatments containing 2,4-D pre-emergence, thifensulfuron post-emergence or fomesafen post-emergence caused crop injury, while the remaining treatment combinations provided excellent volunteer canola control and low crop injury, with similar soybean yield results. The optimal combinations were tribenuron+imazamox+bentazon and saflufenacil+imazamox+ bentazon, as they contain the most herbicide groups, and therefore should be most effective at delaying herbicide resistance. In the cultural control study, soybean was seeded at five different seeding rates (targeted 10, 20, 40, 80 and 160 plants m^{-2}) at three seeding dates (targeted mid-May, late May and early June). Soybean yield consistently increased with higher seeding rates, while volunteer canola biomass decreased, however seeding date results were inconsistent across site-years. An economic analysis determined that the optimal seeding rate was 40-60 plants m^{-2} depending on market price, while the optimal seeding date range was from May 22nd to June 1st.

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DEDICATION

I would like to dedicate this thesis to my parents. Thank you for always believing in me and supporting me in whatever I set out to accomplish. Your unwavering support and encouragement have undoubtedly gotten me to where I am today. You have taught me the value of hard work and to never give up on my goals. I am eternally grateful for all of your sacrifices and unconditional love.

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LIST OF ABBREVIATIONS

a.e. = Acid Equivalent

a.i. = Active Ingredient

ALS = Acetolactate Synthase

ANCOVA = Analysis of Covariance

ANOVA = Analysis of Variance

CHU = Corn Heat Units

CPWC = Critical Period of Weed Control

DAT = Days After Treatment

GDD = Growing Degree Days

GR = Glyphosate Resistant

HSD = Honest Significant Difference

IWM = Integrated Weed Management

LSD = Least Significant Difference

MG = Maturity Group

SC = Seed Contamination

SEM = Standard Error of the Mean

TSW = Thousand Seed Weight

UAN = Urea Ammonium Nitrate

1.0 Introduction

Processed soybean is the world's largest source of protein for concentrated animal feeds and the second largest source of vegetable oil (United States Department of Agriculture, 2012). The oil is used primarily for edible products, but it can also be used in products such as high-grade paints and pharmaceuticals. Soybean meal that remains after the oil is extracted is used as a high protein livestock feed and can be further refined to produce various protein extracts for human consumption (Agriculture and Agri-Food Canada, 2006).

Soybean is a major crop in the United States, with approximately 33.7 million hectares planted in 2016 (United States Department of Agriculture, 2017). The area of soybean grown has been steadily increasing in Canada as well. In 2016, there were approximately 2.21 million hectares of soybean seeded in Canada, with over 97,000 hectares in Saskatchewan. Soybean presents a new cropping option for western Canadian producers, and producer uptake of soybean has been rapid as soybean is a relatively low-input crop providing new opportunities for grain marketing. As a member of the legume family, soybean has the capacity to use fixed atmospheric nitrogen from soil bacteria, which lowers the need for additional nitrogen to be applied by growers. Mean uptake of nitrogen by soybean is estimated to be approximately 219 kg ha^{-1}, with 111 kg ha^{-1} used for nitrogen fixation (Salvagiotti et al. 2008). It was also determined that on average, 50–60% of the nitrogen demand of soybean was met by biological N_2 fixation.

The majority of soybean grown in Canada is grown in eastern Canada (Statistics Canada, 2017). However, soybean production in western Canada has increased significantly in recent years (Table 1.1) (Statistics Canada, 2017), with approximately 97,000 hectares in Saskatchewan and over 661,000 hectares in Manitoba in 2016 (Statistics Canada, 2017). Thus, soybean is rapidly becoming a major crop in western Canada.

Table 1.1. Soybean acreage in western Canada from 2010 – 2016.

Year	Hectares	Average Yield (kg ha^{-1})
2010	210,400	2,100
2011	232,700	1,800
2012	323,700	2,400
2013	493,700	2,400
2014	623,300	2,100
2015	669,800	2,400
2016	758,800	2,700

One of the major challenges associated with growing soybean is weed control, and in western Canada, the control of volunteer canola (*Brassica napus* L.). The majority of soybean grown in the U.S and Canada is glyphosate-resistant (GR), but so is a large portion of the canola acreage in western Canada. Producers cannot use glyphosate alone to control volunteer canola in soybean crops, which can pose problems because few chemical options exist for controlling volunteer canola in soybean crops.

Glyphosate-resistant (GR) soybean was first introduced to the USA in 1996 and to Canada in 1997. In both of these regions, the adoption of this technology has been rapid. Currently, over 90% of the soybean grown in the United States is GR (Dill et al. 2008). Glyphosate-resistant soybean has also become a widely-grown crop, and since the introduction of GR soybean, adoption of GR technology has been rapid in cotton (*Gossypium hirsutum*), maize, and canola (Dill et al. 2008). The rapid adoption rate of GR crops is due to several factors. Glyphosate provides economic broad spectrum weed control. It also increases convenience in herbicide application, which provides economic benefits and flexibility to the producer. Glyphosate can be applied over a wide range of crop stages with little potential for crop injury. GR crops have facilitated the use of conservation tillage systems through the use of post-emergent applied herbicides rather than pre-emergent soil-applied herbicides (Dill, 2005; Beckie et al. 2006). In addition, the wide availability of generic herbicides has reduced glyphosate prices, which in turn makes the adoption of GR crops even more economical for producers (Duke, 2005).

Adoption of GR technology has also been rapid in Canada, with adoption rates in Ontario being nearly parallel to those observed in the United States (Cerdeira and Duke, 2006). It is probable that the vast majority of the soybean acres grown in western Canada are also GR and thus, glyphosate-resistant volunteer canola presents a major challenge to soybean production in western Canada; many growers that would choose to grow GR soybean will likely have grown GR canola. In 2009, 48% of the approximately 6.6 million hectares of canola grown in Canada were GR (Beckie et al. 2011), but glyphosate will not control canola volunteers from GR crops grown in previous years. Therefore, judicious management of these volunteers is required in GR soybean.

This project aims to evaluate methods of managing volunteer GR canola in GR soybean crops through both chemical and cultural means. The objective of the first study was to determine the most effective combination of pre- and post-emergent herbicides to control volunteer GR canola in GR soybean. The objective of the second study was to determine the optimal soybean seeding rate and seeding date for soybean in western Canada to compete with volunteer canola, while being economically feasible for producers. The hypothesis of the herbicide study was that saflufenacil pre-emergent combined with imazamox+bentazon post-emergent would provide the best control of volunteer canola with low crop injury. The hypothesis of the cultural control trial was that soybean competitiveness with volunteer canola would be improved with higher seeding rates and a planting date in mid-May. With this thesis, we hope to provide growers with alternatives to avoid significant yield losses in GR soybean crops due to volunteer GR canola by coupling chemical and cultural control methods.

2.0 Literature Review

2.1 History of Soybean

Soybean *(Glycine max* (L.) Merr.) is a member of the Fabaceae family grown for its oil and protein (Canadian Grain Commission, 2013). Soybean was first grown in France in 1739, in England in 1790 (Hymowitz and Newell, 1981), and was first introduced to the United States in 1765 as green forage, as well as for manufacturing soy sauce and other products for export to England (Hymowitz and Harlan, 1983). For many years, soybean acreage increased slowly in the United States, with only 728,000 hectares grown in 1924. In the 1920s, soybean acreage began to expand in the United States Corn Belt. Disruption of trade routes during WWII resulted in a rapid expansion of soybean acreage in the United States, as the country had previously imported the majority of edible and industrial oils. Soybean was successful as a new crop because there was an immediate need for soybean oil and meal, and it benefitted other crops in a rotation (Iowa State University, 2005).

2.2 Soybean Biology and Agronomics

Soybean is an erect, bushy, herbaceous annual that can reach a height of 1.5 metres (Canadian Food Inspection Agency, 2012). Varieties are given a maturity group rating based on corn heat unit requirements that allows growers to plant varieties best suited to their regions. The maturity group (MG) ratings range from MG000-MGX (Burton, 1997), but MG000-MG00 indeterminate varieties are primarily grown in the northern regions of North America. These varieties continue their vegetative growth throughout the flowering period (Canadian Food Inspection Agency, 2012).

If planted at the optimal time, soybean typically develops 5-7 trifoliates before flowering, which is triggered by day length and temperature changes. Very early-maturing soybean, such as the type grown in Canada, are nearly insensitive to day length as flowering in these varieties is controlled mainly by accumulated heat units. Later-maturing varieties are influenced by day length to a greater extent (Ontario Ministry of Agriculture, Food and Rural Affairs, 2016).

Soybean is almost entirely self-pollinated, and rates of cross pollination are very low (Burton, 1997). A soybean plant can produce as many as 400 pods, with two to twenty pods at a single node. Each pod contains one to five seeds (Canadian Food Inspection Agency, 2012). It is recommended that soybean be seeded when the average soil temperature has reached at least 10 °C. Soybean seedlings can generally tolerate -2°C frost. The recommended seeding depth ranges from 0.75 inches to 1.5 inches (Saskatchewan Pulse Growers, 2016).

2.3 Weed Competition in Soybean Crops

Weed competition can have a significant impact on soybean yield. Weeds compete with crops for light, water, and nutrients (Krausz et al. 2001). The magnitude of loss associated with weed competition is influenced by the competitive ability and density of both the weed and the crop. These factors are, in turn, affected by environmental conditions such as weather, soil conditions, and management practices (van Heemst, 1985). Effects of weed competition are also dependent upon the critical period of weed control (CPWC), which refers to the period in crop growth during which weeds must be controlled to prevent yield losses (Knezevic et al. 2002).

Van Acker et al. (1993) showed that the CPWC in soybean generally consisted of two discrete periods, a critical weed-free period and a critical time of weed removal. The critical weed-free period was relatively short in duration and was determined to last until the fourth node, approximately 30 days after emergence. The critical time of weed removal was variable and ranged from the second node growth stage to the beginning pod growth stage, approximately 9 to 38 days after emergence. The most rapid yield loss due to weed interference occurred from the beginning of the bloom stage (R1) to beginning of the seed-set stage (R5). Halford et al. (2001) determined that the CPWC in no-till soybean began at the first or second node stage (VC-V1) and ended at early flowering (R1). Environmental conditions such as moisture availability may affect weed competition and duration of the critical weed free period. In a study by Jackson et al. (1985), four weeks of competition with weeds did not reduce soybean yield under ample soil moisture conditions, although it did under drought conditions. Similarly, when competing with populations of common ragweed, the critical period for soybean was 2 weeks in a dry year and 4 weeks in a wet year, indicating that environmental conditions during the growing season affect the crop's ability to compete with weeds (Coble et al. 1981).

Effects of weed competition on soybean crops depend heavily on the time of weed removal. Several studies have shown that early season weed control is critical to avoid yield losses in soybean. Barrentine (1974) concluded that early season control of common cocklebur (*Xanthium pensylvanicum* Wallr.) is required for maximum soybean yield, and yield reductions did not occur when common cocklebur was removed during the first 4 weeks following soybean emergence. Eaton et al. (1976) studied the effect of velvetleaf (*Abutilon theophrasti* Medic.), prickly sida (*Sida spinosa* L.), and Venice mallow (*Hibiscus trionum* L.) on soybean yield. All three weed species were most competitive when soybean and weeds were established simultaneously, but weeds seeded at the same time as soybean or later significantly reduced soybean yield. However, when weeds were planted 20, 30, or 40 days after soybean, yields did not differ significantly from yields of the weed-free checks. Similarly, Thurlow and Buchanan (1972) determined that soybean yields were not reduced if soybean was maintained weed free for two weeks or more after planting when competing with sicklepod (*Cassia obtusifolia* L.).

In contrast, Krausz et al. (2001) reported that competition from weeds throughout the growing season reduced soybean yield by 68%, largely due to a decrease in the number of pods per plant. However, early-season weed competition did not reduce soybean height or grain yield, but the predominant weeds in this experiment were grassy weeds. Results may have differed if broadleaf weeds had been more prevalent, as broadleaf weeds can cause greater yield loss in soybean (Nave and Wax, 1971). Shurtleff and Coble (1985) examined the impact of five different broadleaf weeds on soybean yield, height, and leaf area. At a density of 16 weeds per 10 m row, redroot pigweed (*Amaranthus retroflexus* L.*)*, common lambsquarters *(Chenopodium album* L.*)*, common ragweed (*Ambrosia artemisiifolia* L.), and sicklepod (*Cassia obtusifolia* L.) reduced soybean yield by 22%, 15%, 12% and 5%, respectively. Soybean height was also reduced by competition from common cocklebur, common lambsquarters, and sicklepod, and leaf area of soybean was higher at greater distances from the weed for all weed species.

Though it was not examined in the study, Krausz et al. (2001) hypothesized that the maturity requirements of soybean cultivars also may affect their ability to compete with weeds, and later maturing varieties could better compensate for weed competition early in the season. Rose et al. (1984) also reported that later maturing soybean cultivars competed more effectively with weeds than earlier maturing cultivars. Saskatchewan has a relatively short growing season and often growers can only grow very early maturing soybean cultivars, which may make weed competition and control even more difficult, as the previous studies have shown that early maturing cultivars do not compete as effectively with weeds.

2.4 Glyphosate Resistance in Weeds

The overuse of herbicides in modern agriculture has led to the development of herbicide resistance in weeds. Herbicide resistance has been identified in 217 weed species in more than 670,000 fields worldwide (Delye et al. 2013). Resistance has been reported to all major known herbicide modes of action, and no new mode of action has been marketed since 1991 (Delye et al. 2013). Prior to the introduction of GR crops, there were no reports of weeds resistant to glyphosate. As of 2016, however, there were 37 weed species worldwide reported to have glyphosate resistance, 17 of those in the United States (Heap, 2017). When producers adopt GR crops, they often cease using other herbicides, reduce tillage and rely almost exclusively on glyphosate for in-crop weed control, which greatly reduces herbicide diversity (Powles, 2008). Such widespread adoption of GR crops and heavy reliance on glyphosate has exerted significant selection pressure favouring weeds possessing traits enabling survival following glyphosate application (Powles, 2008).

The development of herbicide resistance in weeds is an evolutionary process that is dependent upon key factors, such as selection pressure. Weed populations change in genetic composition in response to selection pressure from repeated treatments with a particular mode of action (Jasieniuk et al. 1996). The change in genetic composition results in an increase in frequency of resistance alleles and resistant individuals, producing weed populations adapted to the intense selection imposed by herbicides (Jasieniuk et al. 1996). However, in order for herbicide resistance to occur, genetic variation for resistance must be present in a weed population. The major source of genetic variation is likely to be gene mutation, which is often occurs spontaneously (Jasieniuk et al. 1996). Glyphosate resistant weed populations are believed to result from both evolved herbicide-resistant weed populations and naturally tolerant weed populations that have developed as a result of the selection pressure imposed by the crop production system (Owen, 2008).

Several different mechanisms have been shown to cause glyphosate resistance. Target site resistance to glyphosate occurs through mutations in the EPSPS gene (Powles and Preston, 2006) that result in the substitution of amino acids of the EPSPS protein, producing modest levels of glyphosate resistance (Healy-Fried et al. 2007). Conversely, non-target site-based (metabolic) resistance to glyphosate has been shown to be the result of a reduction in translocation of glyphosate to the meristematic regions of resistant plants (Powles and Preston, 2006). Both target site and non-target site glyphosate-resistance mechanisms tend to be inherited as nuclear traits (Powles and Preston, 2006). Lorraine-Colwill et al. (2002) identified glyphosate resistance in one *Lolium* population that was the result of reduced translocation of the herbicide to the shoot meristem. Glyphosate was preferentially accumulated in the tips of the leaves of resistant plants, rather than in the shoot meristem and roots, as in susceptible plants. Glyphosate is a very mobile herbicide in plants and relies on translocation to the meristematic regions for its activity (Preston et al. 2009). Reducing the amount of glyphosate translocating to the shoot meristem and roots would reduce inhibition of the shikimate pathway in these tissues to allow the plant to survive a glyphosate application (Preston et al. 2009). Baerson et al. (2002) also hypothesized that the mechanism of glyphosate resistance may be a combination of several processes, including elevated shikimate pathway activity, differential induction of EPSPS activity by glyphosate, as well as reduced herbicide uptake.

2.5 Volunteer Canola as a Weedy Competitor

Glyphosate resistant crops have gained popularity since glyphosate made weed control easier and more effective. These crops require less tillage, do not restrict crop rotation and increase profit (Green, 2009), which has led to GR canola becoming a prevalent weed in western Canada. This poses a challenge for many growers because of the presence of volunteer GR canola in their crop rotation.

One reason that volunteer canola is so prevalent is because of seed losses. The canola seedbank is continually repopulated through harvest losses or seed contamination (Gulden et al. 2003a). Seed losses of canola during harvest can be as high as 3,600 seeds m^{-2} (Gulden et al. 2003b), and volunteer canola has been shown to persist for up to 4 years in rotation in western Canada (Legere et al. 2001). Because of the low seed weight of canola (thousand seed weight ~5 g in western Canada); even small yield losses can result in large additions to the seedbank (Gulden et al. 2003b). In addition, canola seeds are small and of low mass, so seed spillage during seed or field equipment transportation and subsequent dispersal by multiple vectors is a constant challenge that can serve to exacerbate the problem (Beckie and Owen, 2007). Canola also has potential for gene flow, passing the GR trait to non-GR crops or feral populations. For example, in a study by Knispel et al. (2008) examining feral canola, glyphosate resistance was found in 14 (88%), while multiple resistance was observed in 10 (62%) of the tested roadside populations.

Volunteer GR canola is prevalent in areas where canola is grown. Simard et al. (2002) reported volunteer canola plants present in 90% of the fields surveyed in Quebec, and in a wide range of crops including cereals, corn, and soybean. Average densities of 4.9 and 3.9 volunteer plants m^{-2} were observed one year after canola production in fields and field margins. Although volunteer canola densities decreased significantly over time, volunteers were still present at low densities four and five years after production. Gulden et al. (2003b) quantified canola seed losses over two years in 35 fields of 15 different producers. Average yield losses among producers ranged from 3.3 to 9.9%, or 9 to 56 times the normal seeding rate of canola (Canola Council of Canada, 2016). Seed losses of this magnitude could result in the development of substantial volunteer populations, even without further seedbank additions from escaped volunteers.

Little research has been conducted on yield losses in soybean due to volunteer canola. However, several studies have looked at yield losses due to volunteer canola in other crops. O'Donavan et al. (2008) noted that a density of 50 volunteer canola plants m^{-2} reduced wheat (*Triticum aestivum* L.) yield by 29 to 49%. Their results also indicated that volunteer canola had little effect on wheat yield if removed within the first 25 days after wheat emergence, regardless of volunteer canola density. Krato and Peterson (2012) studied the impact of volunteer canola in spring and winter wheat crops. The results showed that the highest volunteer density of 261 plants m^{-2} resulted in a maximum yield loss of 68% in winter wheat. Moreover, a single volunteer canola plant per square meter caused a 0.74 to 1.61% yield loss in the field. Seerey and Shirtliffe (2010) observed an average wheat yield loss of approximately 0.22% per volunteer canola plant, with yield loss increasing to 0.41% per plant when volunteer canola plants were mature. These studies indicate early season control of volunteer canola is critical to avoid significant crop yield losses.

2.6 Weed Control in Soybean Crops

2.6.1 Mechanical Weed Control

Mechanical weed control is an important tool for managing annual and perennial weeds in soybean crops. Two of the predominant methods of mechanical weed control in soybean are inter-row cultivation and rotary hoeing. These methods are used both in organic and conventional systems as part of integrated weed management tactics to reduce herbicide applications. However, mechanical weed control can pose a risk of crop injury in some instances. Buhler et al. (1992) found that one or two inter-row cultivations reduced the amount of herbicide used without reducing weed control or soybean yield. Two passes of a rotary hoe substantially reduced weed densities and increased the effectiveness of subsequent cultivations, but reduced soybean density. They concluded that under low weed densities, mechanical weed control systems resulted in soybean yields similar to the weed-free control. However, under greater weed densities, mechanical weed control systems resulted in reduced soybean yields compared to weed control systems that included herbicides. A study by Buhler (1999) had similar results when several different methods of weed control were used in corn and soybean. Rotary hoeing resulted in higher weed populations and lower crop yield under high weed densities when compared to chemical weed control treatments.

Planting date also may influence the effectiveness of rotary hoeing in soybean. Buhler and Gunsolus (1996) noted that weed control with rotary hoeing and cultivation was often improved by delaying soybean planting. When pre-plant tillage and planting were delayed, weed densities were reduced and mechanical weed control operations resulted in soybean yield similar to the herbicide treatment. However, there is potential for reduced soybean yield with delayed planting. Successful mechanical weed control is directly related to the timeliness of the operation

(Gunsolus, 1990). Rotary hoeing is effective on weeds that have germinated but not yet emerged, although it is not effective on weeds that germinate from deeper than 5 cm, on no-till fields, or on fields with heavy crop residue. Inter-row cultivation is most effective on emerged weeds that are 10 to 15 cm tall (Gunsolus, 1990).

2.6.2 Chemical Weed Control

Although GR soybean receives applications of glyphosate, additional herbicides are sometimes required to provide improved weed control. This may be due to the lack of soil residual activity with glyphosate, which allows weeds to emerge after an application has been made (Johnson et al. 2002). There are also weed species that have developed resistance to glyphosate, such as kochia (*Kochia scoparia* (L.) Schrad.). In addition, the presence of GR volunteer canola can also substantially complicate weed control in soybean.

Currently there are very few herbicides registered for control of GR canola in GR soybean. In Saskatchewan, the only products registered for control of volunteer canola in soybean (post-emergence) are Basagran®/Basagran Forte® (bentazon), Odyssey®/Odyssey Ultra® (imazamox+imazethapyr/imazamox+imazethapyr+sethoxydim) and Viper ADV® (imazamox+bentazon). The only pre-seed/pre-emergence products registered are Focus® (carfentrazone+pyroxasulfone), metribuzin+trifluralin, Heat® (saflufenacil), Express SG® (tribenuron) and 2,4-D. Pursuit® (imazethapyr) and Reflex® (fomesafen) are registered in Manitoba, but not currently in Saskatchewan (Saskatchewan Ministry of Agriculture, 2016). Very limited information exists regarding the efficacy of these products on volunteer canola control when applied to soybean crops, and there are no published studies in the scientific literature that address the issue of managing GR canola in GR soybean. However, many studies have been published addressing herbicide options to control various other weeds in soybean.

A study by York et al. (2004) determined that GR cotton was controlled most effectively in GR soybean by treatments consisting of PRE and POST herbicides applied sequentially, rather than a PRE or POST herbicide only, which provided inconsistent control. Cotton control and fruit reduction were greatest and most consistent with sequential applications of metribuzin+chlorimuron PRE followed by chlorimuron, flumiclorac, fomesafen, or 2,4-D POST (York et al. 2004). Krausz et al. (2001) observed that applications of chlorimuron plus thifensulfuron POST and bentazon plus acifluorfen POST reduced soybean height and chlorosis. However, despite the injury caused by these herbicides, there was no effect on soybean maturity, population, or grain yield. Two experiments using PRE and POST herbicides alone to control GR weed species found that mixing glyphosate with other POST broadleaf herbicides or using soil-applied PRE herbicides after crop planting effectively controlled the weed species studied (Knezevic et al. 2009). Sulfentrazone+chlorimuron and pendimethalin+imazethapyr+imazaquin were the best PRE herbicide treatments and provided residual weed control up to 8 weeks. Glyphosate tank mixes with half of the labeled rates of chlorimuron or acifluorfen were the best POST treatments, providing more than 80% control of all studied weed species when applied to 5 to 15 cm tall weeds (Knezevic et al. 2009).

The addition of other herbicides to glyphosate is also essential for control of weed species that have developed resistance to glyphosate, as well as to prevent further resistance from developing. Canada fleabane (*Conyza canadensis* (L.) Cronq.) has developed resistance to glyphosate in Ontario. A recent study by Byker et al. (2013) determined that pre-planting tank mixes of glyphosate plus saflufenacil or saflufenacil/dimethenamid-p provided greater than 87% control 4 weeks after application. Glyphosate tank-mixed with metribuzin, cloransulam-methyl or flumetsulam provided 78 to 99% control 8 weeks after application. All of these options provided the most consistent control of GR Canada fleabane and did not injure soybean (Byker et al. 2013). Giant ragweed *(Ambrosia trifida* L.) has also developed resistance to glyphosate in Ontario and poses a challenge in GR soybean crops. Vink et al. (2012) determined that the best control of GR giant ragweed was achieved with 2,4-D ester, cloransulam-methyl and saflufenacil applied alone or as a tank mix with glyphosate. These treatments provided 97-99%, 68-100%, and 71-94% control, respectively, and produced soybean yields equivalent to the weed-free check.

2.6.3 Cultural Weed Control

2.6.3.1 Soybean Seeding Rate

i) Weed Competition

Seeding rate can have a substantial effect on weed populations due to its effect on crop density and crop competitiveness. Several studies have evaluated the effect of increasing soybean seeding rates on weed populations. Crops seeded at a higher population density tend to have a competitive advantage over weeds, in part due to rapid canopy development (Guillermo et al. 2009). Accordingly, Norsworthy and Oliver (2001) found that low soybean seeding rates of 185,000 and 247,000 seeds ha^{-1} consistently required a greater number of glyphosate applications due to the lack of early-season canopy formation. In contrast, higher seeding rates of 865,000 up to 1,482,000 seeds ha^{-1} sometimes required only a single application for season-long weed control. Similarly, Guillermo et al. (2009) reported that end-of-season weed biomass decreased linearly as soybean plant population increased at all sites. They also concluded that higher seeding rates increased the competitiveness of soybean with weeds, and reducing crop population may provide a more favourable environment for weed growth. McWhorter and

Barrentine (1975) showed that increased soybean seeding rates increased control of common cocklebur in all cultivars studied, regardless of the cultivar and cultivation method used. Likewise, Nice et al. (2001) determined increased soybean populations of 481,000 to 676,000, along with reduced row spacing, reduced sicklepod (*Senna obtusifolia)* density.

ii) Influence on Crop Yield

Soybean seeding rate can also influence crop yield, due in part to the influence on canopy development and light interception (Lee et al. 2008). Place et al. (2009) noted that increased seeding rates increased soybean yield in both organic and conventional crops in most instances, not only because of improved weed control, but also because of increased light interception. Cox and Cherney (2011) reported a 7% soybean yield increase as seeding rates increased from 321,000 seeds ha^{-1} to 420,000 seeds ha^{-1}, but then declined by 4% as seeding rate increased to 469,000 seeds ha^{-1}. Elmore (1998) found that soybean yield increased by 42% as seeding rate increased from 111,000 to 347,000 seeds ha^{-1} and then remained constant with increased seeding rate. These studies show that soybean yield will increase with increasing seeding rates until a plateau is reached, after which yield begins to decrease. This is known as the law of constant final yield, where total standing plant biomass initially increases in proportion to density, levels off, and then remains constant as density increases further (Weiner and Freckleton, 2010). Carpenter and Board (1997) concluded that yield reduction at high seeding rates is associated with more intense interplant competition in high populations, as well as decreased total dry matter partitioning into branch dry matter. De Bruin and Pederson (2008a) compared soybean yield at four different seeding rates, 185,000; 309,000; 432 000; and 556,000 seeds ha^{-1} and found the maximum soybean yield was attained at a final harvest population of 462,200 plants ha^{-1}. Nevertheless, their data suggested that >95% of the maximum yield was achieved with final populations as low as 258,600 plants ha^{-1}. However, their study combined lower seeding rates with narrow row spacing of 38 cm, which contributed to the higher yields. They also point out that a potential problem with higher seeding rates is the increase in plant competition, which generates stress on the canopy.

The recommended seeding rate for soybean at 15 inch spacing is approximately 437,000 seeds ha^{-1} (Ontario Ministry of Agriculture Food and Rural Affairs, 2016). Because of the law of constant final yield, increasing seeding rates only proves beneficial until the plateau is reached. After that point, no yield benefit is achieved with increasing seeding rates. High seeding rates can also pose agronomic challenges. Plants in dense stands must compete for light, moisture, and nutrients (Pennypacker and Risius, 1999). Higher plant densities also result in conditions that are more conducive to disease increase and spread. Increasing the seeding rate changes the proximity of individual plants and plant parts, which influences the movement of pathogens between plants. Plant stand density also influences air movement, shading, and moisture retention within the canopy (Krupinsky et al. 2002).

2.6.3.2 Soybean Seeding Date

i) Weed Competition

Planting date can also affect the ability of a crop to compete with weeds. Planting early may improve the competitive advantage of the crop, which reduces the adverse effects of weed competition. Altering planting dates may also impact weed emergence patterns (Klingaman and Oliver, 1994). Germination of weed seeds depends on soil temperature, soil moisture, and seed dormancy, and the requirements for suitable germination also differ among weed species (Forcella et al. 1992). Therefore, the effect of delayed planting on weed density tends to vary among species, locations, and years. For example, Oliver (1979) reported that if sown in mid-May, velvetleaf (*Abutilon theophrasti* Medic.) was twice as competitive compared to when sown in late June.

Early planting of crops such as soybean can decrease the competitive ability of the crop with weeds that are adapted to cooler conditions (Liebman et al. 2001). Coulter and Nafziger (2007) found that total weed population density was greatest with early planting dates compared with later planting dates, demonstrating that planting soybean early decreased the crop's competitiveness with weeds. In contrast, Klingaman and Oliver (1994) found that weed interference increased as soybean planting date was delayed, concluding that soybean has a greater ability to interfere with weed growth when planted early in the growing season. This ambiguity may be due to the type of weed being studied, as the predominant weeds in Coulter and Nafziger's study were lambsquarters, giant foxtail (*Setaria faberii)*, and tall morningglory (*Ipomoea purpurea)*, whereas Klingaman and Oliver measured interference by entireleaf morningglory (*Ipomoea hederacea)* and sicklepod. Rushing and Oliver studied interference of common cocklebur when soybean was planted in April, May, and July. For each successive delay in planting date, common cocklebur required two additional weeks to establish canopy dominance and thus, the authors concluded that the soybean competed more effectively with common cocklebur as planting date was delayed. Planting date also had a significant effect on common cocklebur aboveground biomass. Cocklebur biomass was highest with April planting and therefore, delayed soybean planting may diminish the ability of common cocklebur to become a dominant species (Rushing and Oliver, 1998).

ii) Influence on Crop Yield

While delayed planting may be beneficial for weed control, it can also reduce crop yield potential. In Minnesota, delaying soybean planting from May 10 to June 20 reduced soybean yield by 30% (Hardman and Gonsolus, 1994). Similarly, Robinson et al. (2009) reported that delaying planting until late May or early June significantly reduced soybean yield, with the highest yield occurring at planting dates ranging from late April to early May. Research by De Bruin and Pederson (2008b) concurs with these two studies, as no yield differences were observed between soybean planted at the end of April or mid-May across 13 locations in Iowa, however, yield was reduced whenever seeding was delayed beyond mid-May. An additional study observed that both determinate and indeterminate soybean cultivars yielded higher with a May planting date when compared to a July planting date (Parvez et al. 1989). Similarly, Kane et al. (1997) found that when soybean was planted in late April, mid-May, early June, and late June, yields were similar for the first three planting dates but decreased at the late June planting date.

In contrast to these studies, other research has suggested delayed seeding can improve yield potential. Buhler and Gunsolus (1996) reported that the yield of late-planted soybean was greater than early-planted soybean for all treatments, which is contrary to the expected planting response. Reduced yield in the early-planted soybean were likely due to moisture stress that occurred early in the flowering period. Rushing and Oliver (1998) assessed common cocklebur interference in soybean and found a trend towards greater yield reduction in April-planted soybean compared with May or July planting; actual soybean yields in weed-free plots decreased as planting date was delayed from April to July. Pederson and Lauer (2004) examined the effect of planting date on individual soybean yield components, finding that the early May planting date produced higher seed number, pod number, and harvest index but lower seed number per pod than the late May planting date. However, they conclude that the ability of soybean to compensate among yield components is more affected by year variability than by management system and planting date. Egli and Cornelius (2009) examined data from 28 non-irrigated planting date experiments in the United States. The response of yield to delayed planting was similar in all regions with the rapid decline in yield beginning on May 30 in the Midwest, June 7 in the Upper South and May 27 in the Deep South. However, yield trends before the rapid decline began showed no significant advantage for early plantings. Only 23% of the April or early May plantings exhibited higher yields than later seeding dates. The authors concluded that there is no consistent advantage for ultra-early planting dates, but there was a significant penalty for planting after the critical date in late May or early June. The findings of these numerous studies indicate that seeding rate and date can have a substantial effect on managing weeds in soybean crops. These cultural control methods may improve soybean competition with volunteer canola, which is not currently effectively controlled by herbicides.

While the results of these studies are useful in the western Canadian context, many of these studies were conducted across the Midwestern United States, where climate and growing season differs from the Prairies. Soil temperature should be at least 10°C at the time of planting soybean, which generally does not occur before mid-May in Saskatchewan. Therefore, April and early May planting is likely not possible in this region. Some of the studies quoted above also use a July planting date, which is too late for western Canada due to the short growing season. Planting soybean this late in Saskatchewan would likely result in severe frost damage and possible loss of the crop. Therefore, it is essential to determine an optimal planting date for soybean in western Canada that is early enough for the crop to compete with weeds and avoid heavy frost damage, yet late enough that the soil has reached warm enough temperatures for the crop to germinate.

3.0 Evaluating pre- and post-emergence treatments for control of glyphosate resistant canola in glyphosate-resistant soybean

3.1 Introduction

The critical period of weed control in soybean is from the first or second-node stage to early flowering (Halford et al. 2001) or the beginning of pod growth (Van Acker et al. 1993). Several studies have shown that early season weed removal is critical to avoid yield loss in soybean, and weeds that emerge late in the season have no significant negative impact on soybean yield (Thurlow and Buchanan, 1972; Barrentine, 1974; Eaton et al. 1976). The maturity requirements of soybean cultivars also may affect their ability to compete with weeds, as later maturing varieties tend to compete more effectively with weeds (Rose et al. 1984; Krausz et al. 2001). In western Canada, early maturing varieties are grown most widely because of the the short growing season and thus, weed control in soybean is even more critical in these varieties.

Glyphosate resistant (GR) canola (*Brassica napus* L.), a widely-grown crop in western Canada, is also a prevalent weed due to high harvest losses of seed, as well as its ability to persist in the seedbank for several years (Legere et al. 2001; Gulden et al. 2003a). Volunteer canola is also an economically important weed that greatly impacts crop yield potential. For example, volunteer canola reduced yield by up to 49% at densities of 50 plants m^{-2} in wheat (*Triticum aestivum* L.) (O'Donavan et al. 2008). Volunteer canola interference at a density of 261 plants m^{-2} reduced winter wheat yield by 68% (Krato and Peterson, 2012). Moreover, volunteer canola caused an average wheat yield loss of 0.22% per canola plant, increasing to 0.41% when volunteer canola plants were mature (Seerey and Shirtliffe, 2010). These studies show that volunteer canola causes substantial yield loss in cereal crops, but yield losses in soybean (*Glycine max* L.) have not been determined.

Volunteer GR canola is a difficult weed to manage as the canola seedbank is continually replenished through harvest seed losses, which can be as high as 3,600 seeds m^{-2} (Gulden et al. 2003a; Gulden et al. 2003b). Due to the small seed size of volunteer canola, significant amounts of seed return can produce large contributions to the seedbank, and canola seed spillage from field equipment is common (Gulden et al. 2003b; Beckie and Owen, 2007). In addition, volunteer canola seeds can be induced into secondary seed dormancy, which contributes to higher seedbank persistence and volunteer seedling recruitment (Gulden et al. 2003a). GR canola also has potential for gene flow to feral populations, and glyphosate resistance has been found in 88% of roadside canola populations in southern Manitoba (Knispel et al. 2008).

Volunteer glyphosate resistant canola poses a challenge for soybean production, as many growers that choose to grow GR soybean also grow GR canola, and glyphosate alone will not control GR canola in GR soybean. There are very few herbicides registered for control of volunteer GR canola in GR soybean in western Canada. Currently registered herbicides for pre-emergence control of GR canola in GR soybean include acetolactate synthase (ALS) inhibitors (Group 2), synthetic auxins (Group 4) and protoporphyrinogen oxidase (PPO) inhibitors (Group 14). Herbicides registered for post-emergence control include acetolactate synthase (ALS) inhibitors and photosystem II-inhibiting herbicides (Group 6) (Saskatchewan Ministry of Agriculture, 2016). However, very limited information exists regarding the efficacy of these products on volunteer canola in soybean crops.

Although there is very little research regarding control of volunteer GR canola in GR soybean crops, there are various studies examining control of other GR volunteers in GR soybean. For example, to control volunteer GR cotton (*Gossypium hirsutum*. L.) in soybean, sequential applications of metribuzin+chlorimuron pre-emergence followed by chlorimuron, flumiclorac, fomesafen, or 2,4-D post-emergence were most effective (York et al. 2004). With regard to volunteer GR corn (*Zea mays* L.) in GR soybean, glyphosate tank mixed with quizalofop-p-ethyl, clethodim, or fenoxaprop-p-ethyl effectively controlled volunteer GR corn and caused no injury to soybean (Deen et al. 2006). Another study reported that clethodim, fenoxaprop-p-ethyl, fluazifop-p-butyl and quizalofop-p-ethyl all provided good control of volunteer GR corn and caused little injury to soybean when mixed with glyphosate (Soltani et al. 2006).

Studies have also focused on controlling weeds in GR soybean that have developed resistance to glyphosate. Pre-emergence tank-mixes of glyphosate plus saflufenacil or saflufenacil/dimethenamid-p and glyphosate tank-mixed with metribuzin, cloransulam-methyl or flumetsulam provided good control of GR Canada fleabane (*Conyza canadensis* L.) and did not injure soybean (Byker et al. 2013). GR giant ragweed (*Ambrosia trifida* L.) was controlled in GR soybean with 2,4-D ester, cloransulam-methyl and saflufenacil applied alone or as a tank mix with glyphosate (Vink et al. 2012). Although injury levels in Vink et al. (2012) were above the acceptable threshold, fomesafen tank mixed with glyphosate has been shown to provide control of some GR weeds in soybean, including GR giant ragweed (Brabham et al. 2011) and GR common ragweed (*Ambrosia artemisiifolia* L.) (Van Wely et al. 2015).

The prevalence of GR volunteer canola in western Canada, as well as the lack of literature regarding management of GR canola in GR soybean, presents a formidable challenge for producers. Producers need better options for managing GR canola volunteers in GR soybean crops. The present study was conducted to evaluate the efficacy of various pre- and post-emergence herbicides applied sequentially to volunteer GR canola, and to evaluate soybean injury caused by these herbicides. The hypothesis of this study was that sequential applications of saflufenacil applied pre-emergence and imazamox+bentazon applied post emergence would produce the best control of volunteer canola, with minimal crop injury.

3.2 Materials and Methods

3.2.1 Site Description

Field experiments were conducted in 2014 and 2015 at the Kernen Crop Research farm (52°15’ N, 106°53’ W) at Saskatoon, SK, at the Western Applied Research Corporation (52°21’ N, 108°49’ W) in Scott, SK, at the Indian Head Agricultural Research Foundation (50°31’ N, 103°39’ W) research farm at Indian Head, SK, and at the University of Manitoba Research Farm (49°30’ N, 98°00’ W) at Carman, MB. Saskatoon and Scott are located in the Dark Brown soil zone, while Indian Head and Carman are located in the Black soil zone. Soil descriptions are presented in Table 3.1.

Table 3.1. Soil classification and descriptions for each site-year.

Site-year	Soil type	Soil descriptions				
		pH	OM (%)	Sand (%)	Silt (%)	Clay (%)
Saskatoon 2014	Dark Brown Chernozem	7.9	2.4	19	36	45
Scott 2014	Dark Brown Chernozem	5.8	3.1	29	53	18
Indian Head 2014	Black Chernozem	7.4	3.4	13	21	66
Carman 2014	Black Chernozem	5.5	6.0	54	15	31
Saskatoon 2015	Dark Brown Chernozem	7.9	2.4	19	36	45
Scott 2015	Dark Brown Chernozem	5.6	5.3	31	59	11
Indian Head 2015	Black Chernozem	7.4	3.4	13	21	66
Carman 2015	Black Chernozem	5.5	6.0	54	15	31

3.2.2 Experimental Procedures

The experimental design was a randomized complete block design (RCBD) with 16 treatments and four replications. Treatments consisted of 15 different combinations of pre- and post-emergence herbicides, as well as 450 g ae ha^{-1} glyphosate applied alone as a control treatment (herbicide standard). Plots at Saskatoon and Scott were 2 m wide x 6 m long, while plots at Indian Head measured 4 m wide x 10.7 m long; plots at Carman were 2.5 m wide x 8 m long. Border plots were seeded along the sides of the trial at all locations. Soil samples were taken at depths of 0-15, 15-30 and 30-60 centimeters to determine nutrient levels in the soil, as well as pH and organic matter. No fertilizer was added as nutrient levels in the soil were adequate at the time of sampling at all site-years.

To simulate volunteer canola, canola (cv. Dekalb 72-65 RR) was cross-seeded across the trial at a target density of 40 plants m^{-2} to supplement the established seedbank and to allow for emergence of canola prior to application of the pre-seed herbicide treatments. Canola seed was pre-treated with Acceleron®, a combination of Helix Xtra (difenoconazole+metalaxyl+fludioxonil+thiamethoxam) and Acceleron DX-910 (*Bacillus subtilis*) applied at respective rates of 1500 and 160 ml 100 kg^{-1} of seed, respectively. In addition, another 20 seeds m^{-2} of canola were broadcast across the trial following application of the pre-seed herbicide treatments to supplement the volunteer canola population.

The soybean cultivar used for the study was P001T34R, a Pioneer Hi-Bred 00 maturity glyphosate resistant variety. It was one of the earliest maturing cultivars tested in western Canada at the time of trial initiation. Soybean seed was pre-treated with Cruiser Maxx Vibrance Beans®, a co-pack of Cruiser Maxx Beans (thiamethoxam+ +fludioxonil+metalaxyl) and Vibrance 500 FS (sedaxane), applied at rates of 195 mL + 10 mL 100 kg^{-1} of seed, respectively.

Soybean seed was pre-inoculated with Optimize® inoculant (*Bradyrhizobium japonicum)*, and granular TagTeam (*Pencillium bilaii*) was applied at the time of seeding at a rate of 3 kg ha^{-1}. Soybean was sown using a Monosem Vacuum Planter with disc openers spaced at 40 cm at Saskatoon, while plot seeders equipped with hoe openers (Scott, Indian Head) or disc openers (Carman) were used at other locations.

Pre-emergence herbicide treatments were applied when volunteer canola reached the 1-2 leaf stage. Soybean was then sown 5-7 d after pre-seed herbicide applications at a target density of 444,600 plants ha^{-1} (40 plants m^{-2}) and at a 3 cm seeding depth. Post-emergence herbicide treatments were applied at the 1-2 trifoliate crop stage of soybean (Table 3.2). All pre- and post-emergence treatments were tank-mixed with a 450g ae ha^{-1} rate of glyphosate. Merge® (50% surfactant blend; 50% petroleum hydrocarbons solvent) was added to all saflufenacil treatments at 0.5 L ha^{-1}. UAN (urea ammonium nitrate, 28-0-0) was added to all imazamox+bentazon and cloransulam-methyl treatments at 2 L ha^{-1}. Agral 90 (92% nonylphenoxy polyethoxy ethanol) was added to all fomesafen, thifensulfuron, and cloransulam-methyl treatments at recommended rates. All herbicides were applied with a tractor-mounted sprayer equipped with Airmix 100-015 nozzles calibrated to deliver a volume of 100 L ha^{-1} at 275 kPa. A protocol error resulted in the rate of thifensulfuron being higher than the recommended rate for use on soybean.

Table 3.2. Pre- and post-emergent herbicides and application rates for volunteer GR canola control in GR soybean.

Treatment	Pre-seed Product	Group	Rate	Post-emergent Product	Group	Rate
1	Glyphosate	9	450 g ae ha^{-1}	NONE		NONE
2	2,4-D LV700 Ester	4	550 g ai ha^{-1}	Bentazon	6	1080 g ai ha^{-1}
3	2,4-D LV700 Ester	4	550 g ai ha^{-1}	Fomesafen	14	140 g ai ha^{-1}
4	2,4-D LV700 Ester	4	550 g ai ha^{-1}	Imazamox+bentazon	2+6	449 g ai ha^{-1}
5	2,4-D LV700 Ester	4	550 g ai ha^{-1}	Thifensulfuron (DPX-M6316)	2	11 g ai ha^{-1}
6	2,4-D LV700 Ester	4	550 g ai ha^{-1}	Cloransulam-methyl	2	21 g ai ha^{-1}
7	Tribenuron	2	10 g ai ha^{-1}	Bentazon	6	1080 g ai ha^{-1}
8	Tribenuron	2	10 g ai ha^{-1}	Fomesafen	14	140 g ai ha^{-1}
9	Tribenuron	2	10 g ai ha^{-1}	Imazamox+bentazon	2+6	449 g ai ha^{-1}
10	Tribenuron	2	10 g ai ha^{-1}	Thifensulfuron (DPX-M6316)	2	11 g ai ha^{-1}
11	Tribenuron	2	10 g ai ha^{-1}	Cloransulam-methyl	2	21 g ai ha^{-1}
12	Saflufenacil	14	18 g ai ha^{-1}	Bentazon	6	1080 g ai ha^{-1}
13	Saflufenacil	14	18 g ai ha^{-1}	Fomesafen	14	140 g ai ha^{-1}
14	Saflufenacil	14	18 g ai ha^{-1}	Imazamox+bentazon	2+6	449 g ai ha^{-1}
15	Saflufenacil	14	18 g ai ha^{-1}	Thifensulfuron (DPX-M6316)	2	11 g ai ha^{-1}
16	Saflufenacil	14	18 g ai ha^{-1}	Cloransulam-methyl	2	21 g ai ha^{-1}

Volunteer canola control efficacy was assessed throughout the growing season by visual ratings taken at 7-10, 21-28 and 56 days after the post-emergence treatments (DAT). Visual ratings were taken by comparing treated plots to check plots that had only been sprayed with glyphosate and assessing chemical efficacy on canola plants. Ratings were conducted based on the Canadian Weed Science Society (CWSS) 0-100% scale (Canadian Weed Science Society, 2013), where values greater than 80% indicate acceptable control (Table 3.3).

Table 3.3. CWSS visual efficacy scale for weed control.

Activity Range	Description of Control	Suggested Interval Size
91-100%	Very good to excellent	2%
81-90%	Good to very good	5%
80%	Just acceptable	
70-79%	Suppression	5%
60-69%	Not Acceptable	5%
<60%	Poor	10%

Soybean phytotoxicity was evaluated by visually rating plots on the CWSS scale at 7-10 and 21-28 DAT. Ratings were determined by comparing treated plots to check plots that had only been sprayed with glyphosate and assessing any crop damage (chlorosis, stunting) after herbicide applications. Each treatment was assigned a rating from 0-100% with a rating of 0% indicating no injury and 100% indicating complete mortality. Initial damage of up to 10% is considered acceptable (Table 3.4).

Table 3.4. CWSS visual efficacy scale for crop injury (phytotoxicity).

Phytotoxicity Range	Assessment of Injury	Suggested Interval Size
0-9%	Slight discoloration and/or stunting	2%
10%	Just acceptable	5%
11-30%	Not acceptable	5%
>30%	Severe	10%

Soybean plant stands were assessed by counting plants in two, 1-m rows at 14 and 21 d after emergence in the front, middle and back of each plot. Canola stand density was evaluated before pre-seed and post-emergence herbicide applications in three randomly placed 0.5 m^2 quadrats per plot. Crop and weed biomass sampling was conducted at the pod stage of canola development. Shoot biomass samples (both species) were collected in two 0.5 m^2 quadrats per plot from the front and back of each plot. Samples were cut above just above the ground surface and the canola and soybean were separated and placed in paper bags. All material was oven dried at 80°C for 72 hours and then weighed. Crop height was measured just prior to biomass sampling by measuring the distance from the ground to the top of the plant for 5-10 plants per plot.

Plots were harvested with a small plot combine and all samples were dried to 8% moisture content. Soybean is considered dry at 14% moisture content and thus, yields were adjusted to 14% moisture content. Dried samples were then cleaned and weighed to determine final yield. Thousand seed weight was determined by weighing 250 soybean seeds and multiplying by four. Canola seeds that were cleaned out of soybean samples were also weighed to determine volunteer canola seed contamination. This was determined by calculating the percentage of canola seed in the harvested soybean sample after samples were cleaned and separated.

3.2.3 Statistical Analysis

To ensure the residuals met the assumptions of ANOVA, the Shapiro-Wilk statistic in PROC UNIVARIATE was used to assess normality and the Levene's test was used to assess homogeneity of variance. Additional analysis of the distribution of residuals and variance homogeneity was conducted by using the RESIDUAL statement in PROC MIXED (SAS Inst., 2014).

Analysis of Variance (ANOVA) was performed using the PROC MIXED procedure of SAS 9.3 for all variables, with the exception of canola biomass (SAS Inst., 2014). Due to heterogeneity between sites for soybean biomass, datum was modelled using the REPEATED statement, but this model resulted in a much higher AIC and poorer model fit. Therefore, the original PROC MIXED model was used.

For the one-way ANOVA, treatment was considered a fixed effect, while random effects were site, block nested within site, and site*treatment interactions. Covariance parameters were examined using the COVTEST command of PROC MIXED to determine if site-years could be combined and if conclusions could be drawn from a broader (population-based) inference space. Means for treatment ratings were separated using $LSD_{0.05}$ values. Means for plant height, soybean biomass, yield, thousand seed weight and canola seed production were separated using Tukey's $HSD_{0.05}$. Letter groupings were made with PDMIX800 macro in SAS (Saxton, 1998). ESTIMATE statements were used to determine effects of pre-emergence treatments alone on variables.

Due to many zeros in the data set, canola biomass did not have a normal distribution. Modelling canola biomass in PROC GLIMMIX (SAS 9.3) as a lognormal distribution, with an identity-link resulted in a significantly lower AIC than the original model and corrected for normality and heterogeneity. Canola biomass means were separated using Tukey's $HSD_{0.05}$. Canola biomass means were back-transformed for the purpose of reporting.

Data from Indian Head (2015) were omitted from analysis due to missing and incorrect values. In addition, flooding at Indian Head in 2014 meant it was not possible to collect biomass and harvest data on the third and fourth replications and thus, only data from the remaining two replications were collected.

3.2.3.1 Economic Analysis

Herbicide costs used in the economic analysis are 2016 retail prices for each product (Cargill AgHorizons, 2016, personal communication). Costs of adjuvants or UAN are not included in analysis as these could not be obtained. The cost of glyphosate in addition to pre- and post-emergence herbicides also is not included, as the same rate of glyphosate was used with all treatments in this experiment and would therefore produce the same additional cost for each combination treatment. Gross income and contribution margin was also calculated for each herbicide treatment, using soybean yield and market price ($0.44 per kilogram), which is an average number based on the market price projection for 2016 of $0.39 per kilogram (Saskatchewan Crop Insurance Corporation, 2016), current market price of $0.42 (Rayglen Commodities, 2016) and average market price of $0.49 from 2013, 2014 and 2015 (Agriculture and Agri-Food Canada, 2016). Gross income was calculated by multiplying each soybean yield by market price. Contribution margin was calculated by subtracting total herbicide cost from gross income.

3.3 Results

3.3.1 Environmental Conditions

In 2014, the average temperature was lower (0.3-0.8°C) at all sites than the long-term average temperature (Table 3.5). Total precipitation in 2014 was lower than the long-term average, with the exception of Indian Head, which was much higher than average. In 2015, the average temperature was higher (0.2-0.8°C) at all sites than the long-term average, with the exception of Indian Head, which was on par with the long-term average temperature (Table 3.5). When compared to the long-term average, precipitation was variable across sites throughout all summer months. Overall, total precipitation in 2015 was slightly lower at Saskatoon when compared to the long-term average, and slightly higher at Scott and Carman.

Table 3.5. Mean monthly temperature and precipitation data for Saskatoon, Scott and Indian Head SK, and Carman, MB in 2014 and 2015.

Location	Year	May	June	July	August	September	Avg./Total
	------------------------------ *Mean Temperature (°C)* ---------------------------						
Saskatoon	2014	10.1	14.1	18.3	17.9	12.4	14.6
	2015	11.3	18.1	20.1	18.6	12.9	16.2
	Long term[z]	11.8	16.1	19.0	18.2	12.0	15.4
Scott	2014	9.2	13.9	17.4	16.8	11.2	13.7
	2015	9.3	16.0	18.1	16.8	11.0	14.2
	Long term[z]	10.8	15.3	17.1	16.5	10.4	14.0
Indian Head	2014	10.2	14.4	17.3	17.4	12.3	14.3
	2015	10.0	16.2	18.1	17.0	12.2	14.7
	Long term[z]	10.8	15.8	18.2	17.4	11.5	14.7
Carman	2014	10.0	17.0	18.5	19.9	13.1	15.7
	2015	10.7	17.5	19.9	18.3	15.8	16.4
	Long term[z]	11.6	17.2	19.4	18.5	13.4	16.0
	--------------------------------*Precipitation (mm)*--------------------------------------						
Saskatoon	2014	61.1	94.8	44.5	18.5	10.7	229.6
	2015	6.3	20.2	85.1	58.2	50.8	220.6
	Long term[z]	36.5	63.6	53.8	44.4	38.1	236.4
Scott	2014	23.1	60.4	80.9	30.1	23.6	218.1
	2015	4.1	19.4	46.4	74.5	49.6	194.0
	Long term[z]	36.3	61.8	72.1	45.7	36.0	251.9
Indian Head	2014	36.0	199.2	7.8	142.2	42.3	427.5
	2015	15.6	38.3	94.6	58.8	67.8	275.1
	Long term[z]	51.7	77.4	63.8	51.2	35.3	279.4
Carman	2014	5.4	65.0	31.8	142.2	19.6	264.0
	2015	98.8	75.3	109.3	47.3	42.0	372.7
	Long term[z]	69.6	96.4	78.6	74.8	49.0	368.4

[z]1981 – 2010 Canadian Climate Normals obtained from Environment Canada (2016)

3.3.2 Efficacy Ratings

There were significant site*treatment interactions for efficacy ratings (Table 3.6), but the contribution of site*treatment covariance parameter estimates to total variance was relatively low (13-18%). This, coupled with numerical trends that were similar between sites, led to data being combined across sites.

At 7-10 days after treatment (DAT) for the post-emergence treatments, the highest efficacy was observed with treatments of tribenuron+fomesafen, followed by 2,4-D+fomesafen and saflufenacil+fomesafen (Figure 3.1). These treatments provided 96%, 93% and 91% control of volunteer canola, respectively, showing that fomesafen has very high efficacy and rapid activity immediately following application. However, most treatments had an efficacy above the 80% threshold required for control, with the exception of tribenuron+thifensulfuron, saflufenacil+thifensulfron and saflufenacil+cloransulam-methyl, which had efficacy ratings of 77%, 76% and 75%, respectively (Figure 3.1).

Table 3.6. ANOVA results (P-values) for efficacy at 7-10 DAT, 21-28 DAT and 56 DAT of post-emergent herbicide (Ef7-10, Ef21-28, Ef56) and phytotoxicity at 7-10 DAT and 21-28 DAT of post-emergent herbicide (Phy7-10 and Phy21-28).

Source	Ef7-10	Ef21-28	Ef56	Phy7-10	Phy21-28
			P-value		
Trt	<.0001***	<.0001***	<.0001***	<.0001***	.0116*
Site[a]	.0452*	.0448*	.0435*	.0695	.0928
Site*Trt[a]	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***

*, **,*** , significant at the 0.05, 0.01, and 0.001 probability levels. NA denotes not applicable.
[a] P-values for random effects were assessed using the Wald Z Test (COVTEST).

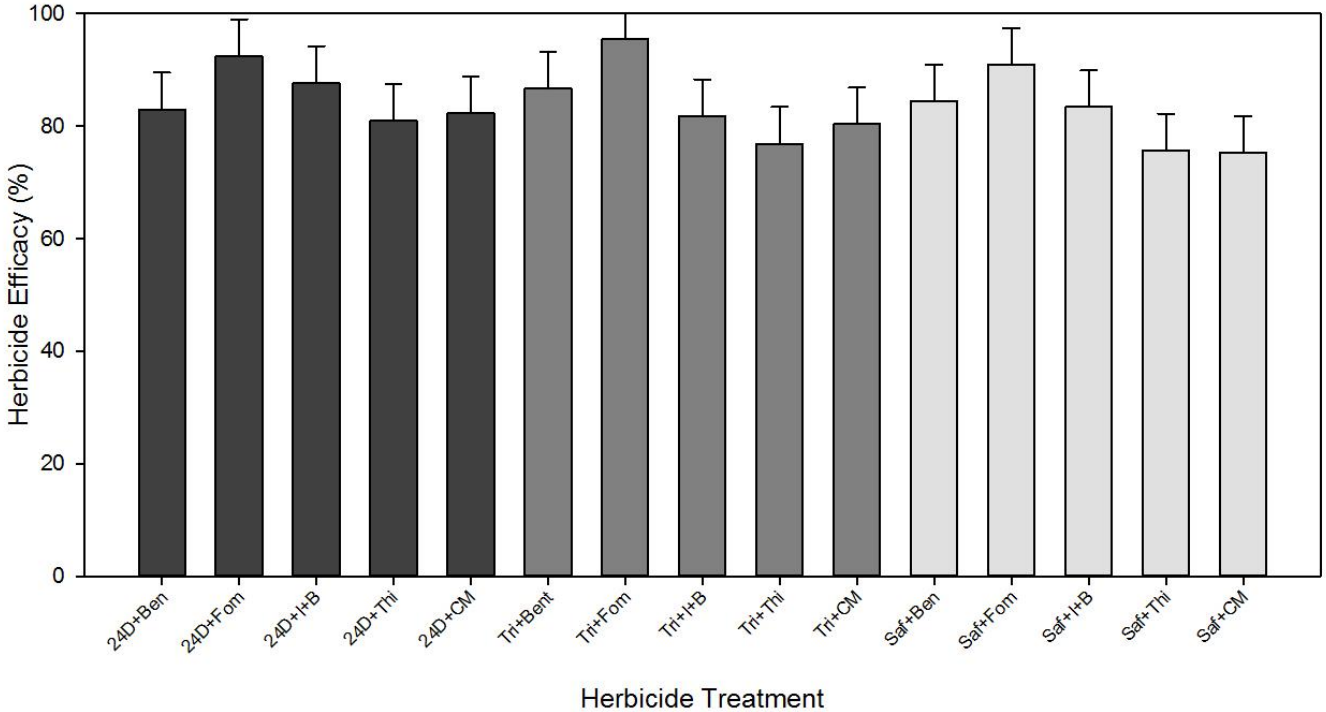

Figure 3.1. Herbicide efficacy on volunteer canola at 7-10 DAT of the post-emergence herbicide. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

By 21-28 DAT, all treatments were at or above 80% control, with the exception of saflufenacil+bentazon, which provided 79% control (Figure 3.2). 2,4-D + cloransulam-methyl was the most effective treatment, exhibiting almost 95% control, and it was followed by 2,4-D+imazamox+bentazon (92% control). All remaining treatments ranged from 80-89% control (Figure 3.2). Treatments containing imazamox+bentazon, thifensulfuron, or cloransulam-methyl applied post-emergence generally had higher efficacy ratings at 21-28 DAT than at 7-10 DAT, while the efficacy of treatments containing bentazon or fomesafen was lower at 21-28 DAT compared to 7-10 DAT (Figure 3.2).

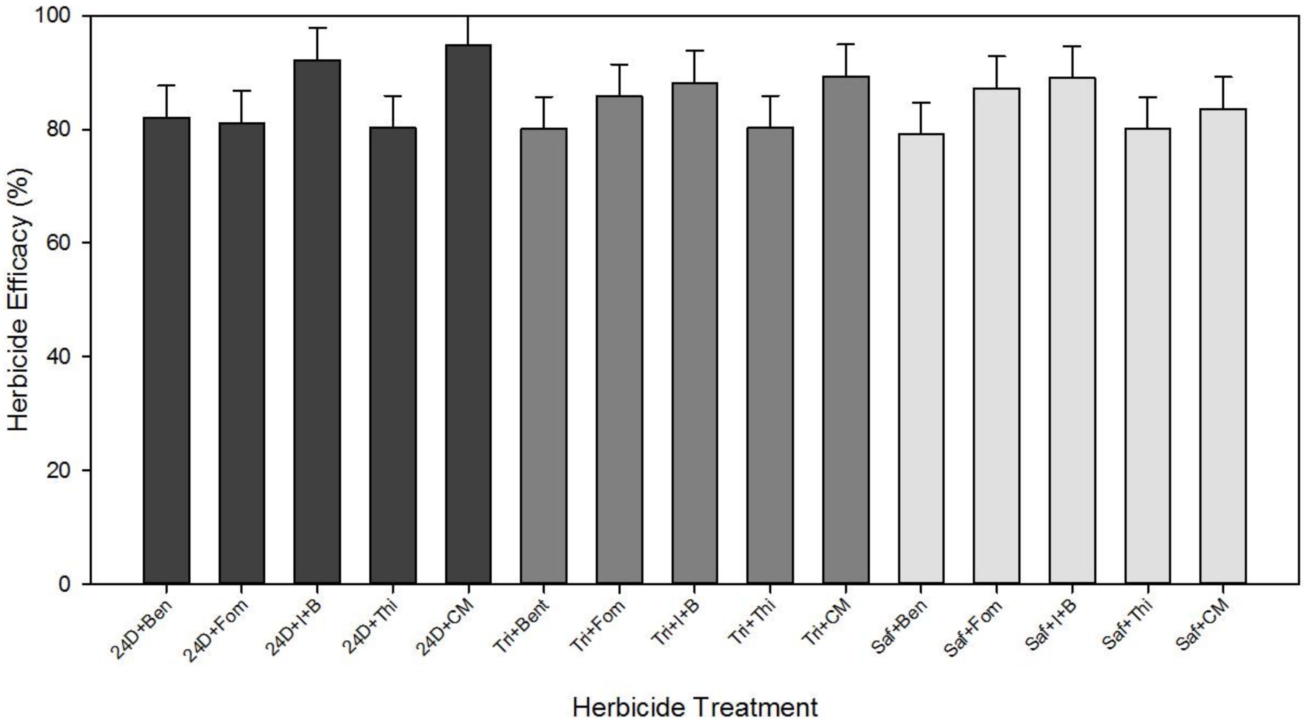

Figure 3.2. Herbicide efficacy on volunteer canola at 21-28 DAT of the post-emergence herbicide. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

By 56 DAT, half of the herbicide treatments had dropped to below 80% control (Figure 3.3). Treatments remaining above 80% control included 2,4-D+imazamox+bentazon, tribenuron+imazamox+bentazon, tribenuron+cloransulam-methyl, saflufenacil+imazamox+bentazon, saflufenacil+cloransulam-methyl and 2,4-D+bentazon. The three lowest efficacies were observed in the three treatments containing post-emergence thifensulfuron, despite thifensulfuron being applied at a high rate. Imazamox+bentazon and cloransulam-methyl provided the longest lasting control of all post-emergence treatments, regardless of which pre-emergence product was used.

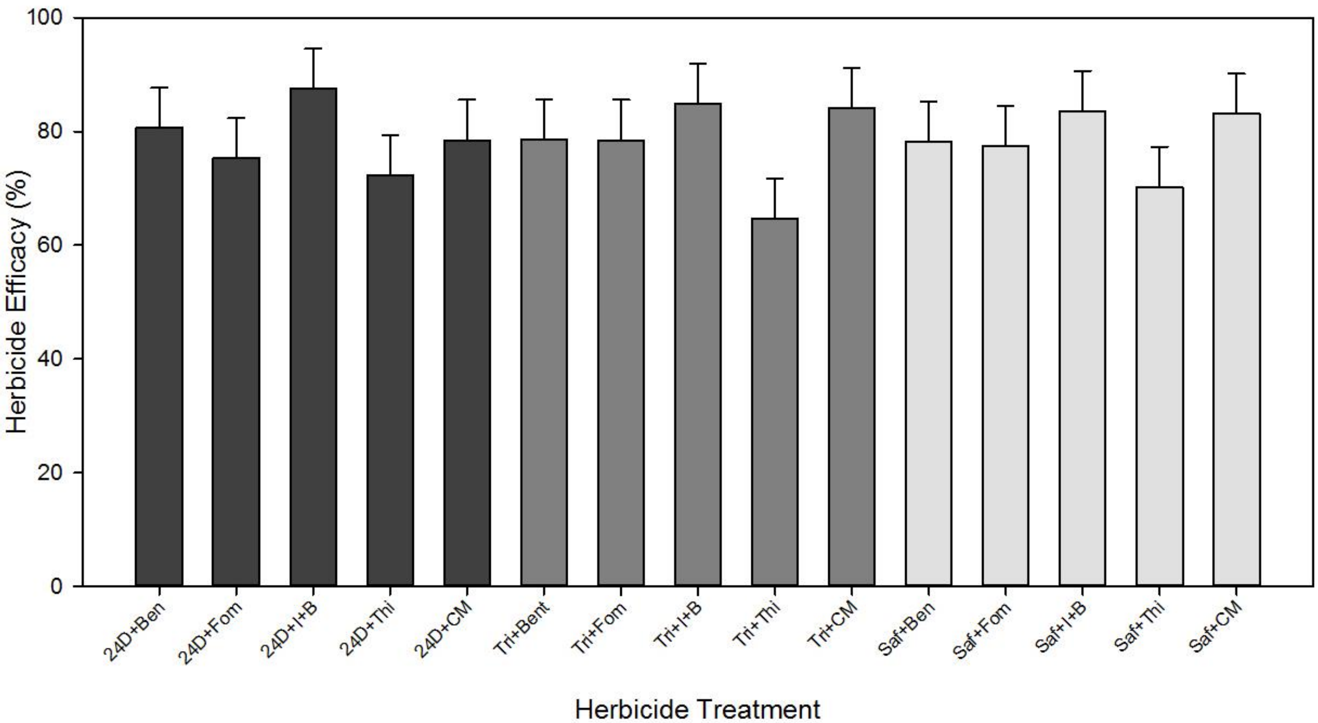

Figure 3.3. Herbicide efficacy on volunteer canola at 56 DAT of the post-emergence herbicide. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

3.3.3 Phytotoxicity (Crop Injury) Ratings

There was a significant site*treatment interaction for phytotoxicity ratings (Table 3.6). Crop injury at 7-10 DAT varied between sites, with overall mean injury less than 5% at Scott in 2014 and 2015, but much higher injury (15-25%) at the remaining locations (data not shown). Trends at the locations with high crop injury ratings were similar. At 7-10 DAT, the three treatments containing thifensulfuron as the post-emergence herbicide had the highest phytotoxicity ratings, exhibiting approximately 28-30% crop injury (Figure 3.4). These ratings are significantly higher than the acceptable threshold of 10% crop injury. These treatments were followed in sequence by treatments containing fomesafen as the post-emergence herbicide, where phytotoxicity ratings of approximately 14%, 15% and 19% were observed. The next three highest ratings were observed with 2,4-D+bentazon, 2,4-D+imazamox+bentazon and 2,4-D+cloransulam-methyl, as crop injury ratings for these treatments were 14%, 10% and 10%, respectively (Figure 3.4).

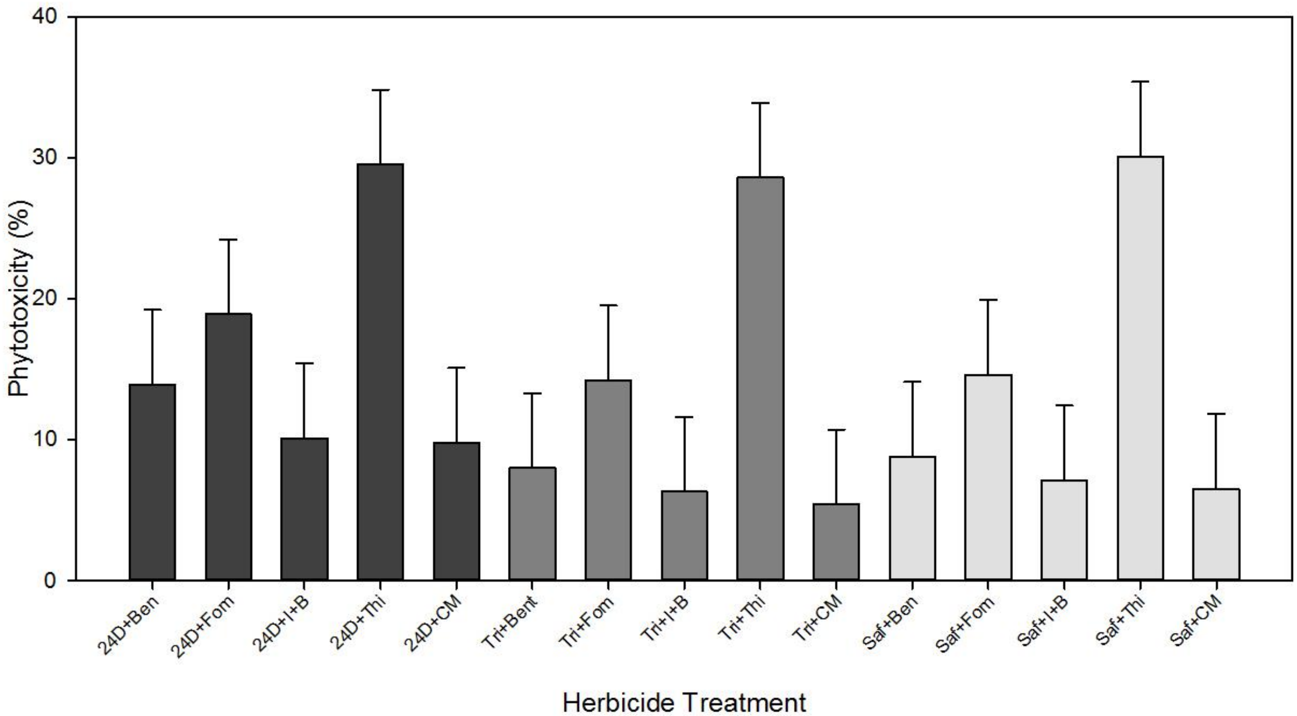

Figure 3.4. Herbicide visual phytotoxicity on soybean at 7-10 DAT of the post-emergence herbicide. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

At 21-28 DAT, there was negligible crop injury recorded at Scott in 2014 and 2015, and mean crop injury ranged from 7-17% at the remaining site-years (data not shown). However, trends were similar between site-years and were therefore combined. At 21-28 DAT, the three treatments containing thifensulfuron again caused the most crop injury, exhibiting phytotoxicity ratings in excess of the 10% threshold (Figure 3.5). However, by 21-28 DAT, the remaining four 2,4-D treatments had phytotxicity ratings that ranged from 8% to 11%. Bentazon, fomesafen, imazamox+bentazon and cloransulam-methyl all had higher crop injury ratings at both 7-10 DAT and 21-28 DAT when applied in a tank-mix with 2,4-D compared to when applied with tribenuron or saflufenacil (Figure 3.5). At 21-28 DAT, treatments with tribenuron or saflufenacil as the pre-emergence treatment had phytotoxicity ratings below 10%, with the exception of treatments containing thifensulfuron applied post-emergence. Phytotoxicity ratings were not done at Carman in 2014 and therefore, this site-year is not included in phytotoxicity results.

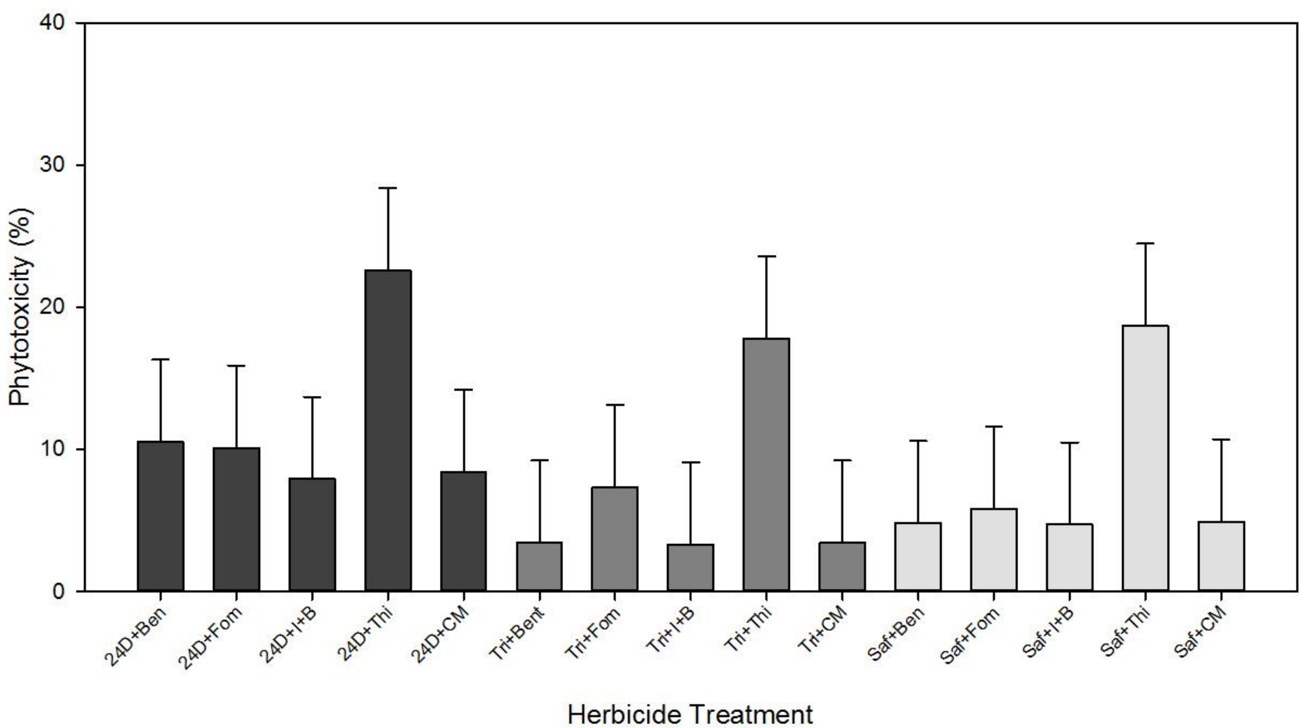

Figure 3.5. Herbicide visual phytotoxicity on soybean at 21-28 DAT of the post-emergence herbicide. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1standard error of mean.

3.3.4 Soybean Shoot Biomass and Seed Yield

Site-years were combined for soybean shoot biomass because the contribution of the site*treatment covariance parameter estimate was less than 10% of the total variance (data not shown). Herbicide treatment was significant for soybean shoot biomass and yield (Table 3.7). The highest soybean shoot biomass (3740 kg ha^{-1}) was observed in treatments of 2,4-D+imazamox+bentazon, which resulted in 226% more soybean shoot biomass than glyphosate alone (1147 kg ha^{-1}) (Figure 3.6). High soybean shoot biomass was also observed in treatments of tribenuron+bentazon, tribenuron+fomesafen, tribenuron+cloransulam-methyl, tribenuron+imazamox+bentazon, saflufenacil+imazamox+bentazon and saflufenacil+cloransulam-methyl, all of which did not differ significantly from each other (Figure 3.6, Appendix 1). These treatments produced 96-99% as much soybean shoot biomass as 2,4-D+imazamox+bentazon. These seven treatments, as well as saflufenacil+fomesafen, each resulted in over three-fold greater soybean shoot biomass compared with glyphosate alone.

The majority of treatments did not differ significantly from each other (Appendix 1), with the exception of 2,4-D+thifensulfuron and glyphosate alone (Figure 3.6). Other than glyphosate applied alone, the three lowest shoot biomass values were observed with the three treatments containing thifensulfuron as the post-emergence herbicide. Treatments of 2,4-D+thifensulfuron resulted in 40% lower soybean shoot biomass (2251 kg ha^{-1}) compared to 2,4-D+ imazamox+bentazon, which had the greatest soybean shoot biomass.

Table 3.7. ANOVA results (P-values) for soybean height, biomass, yield and TSW; and canola biomass and seed contamination.

	Soybean				Canola	
Source	Height	Biomass	Yield	TSW	Biomass	Seed Contamination
	P-value					
Trt	.2425	<.0001***	<.0001***	.380	.0003**	<.0001***
Site[a]	.0596	.062	.0897	.0437*	.1252	.1034
Site*Trt[a]	<.0001***	.0003**	<.0001***	<.0001***	.0009**	<.0001***

*, **,*** , significant at the 0.05, 0.01, and 0.001 probability levels. NA denotes not applicable.
[a] P-values for random effects were assessed using the Wald Z Test (COVTEST).

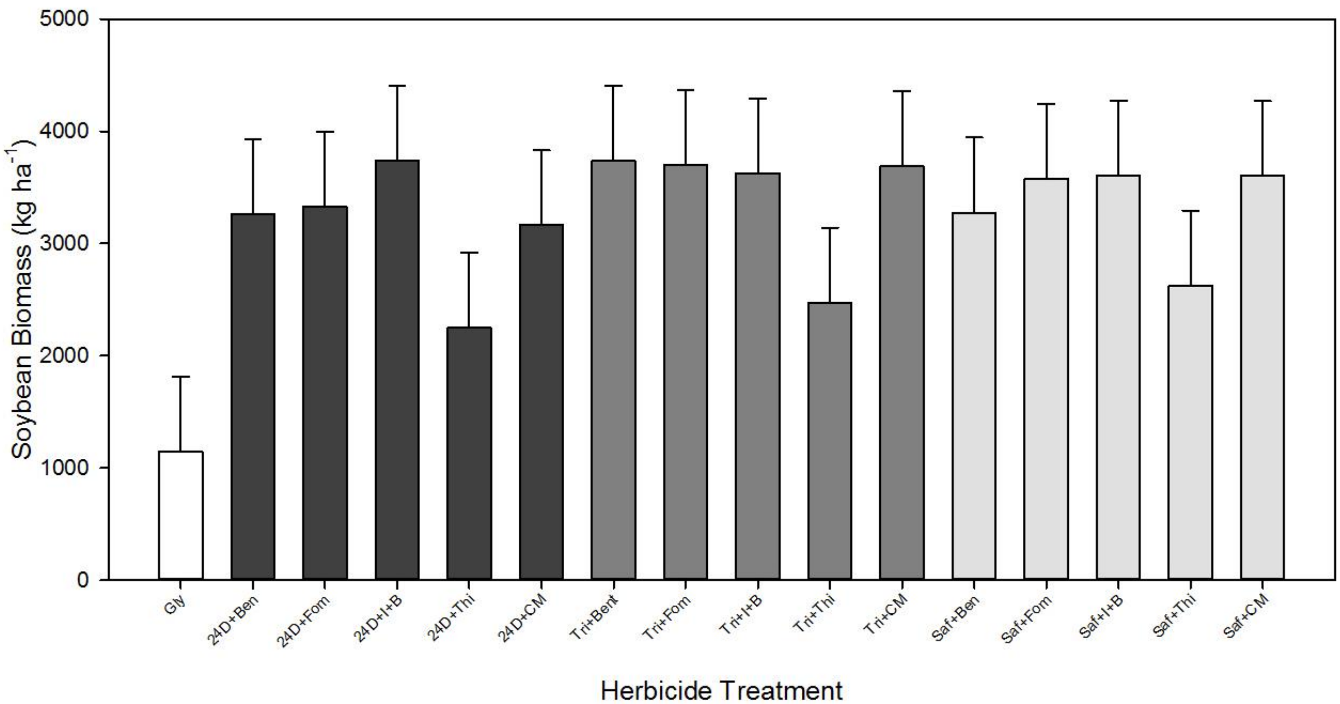

Figure 3.6. The effects of herbicide combinations on soybean dry weight shoot biomass. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

The site*treatment covariance parameter contributed 19% to total variance for soybean seed yield and therefore, site-years were combined. Herbicide treatment had a significant effect on soybean seed yield (Table 3.7). The greatest soybean seed yield occurred with the tribenuron+bentazon treatment, which also had the second highest soybean shoot biomass (Figure 3.7). This treatment produced soybean seed yield of 1448 kg ha^{-1}. Following this treatment were the tribenuron+cloransulam-methyl, saflufenacil+fomesafen and tribenuron+fomesafen treatments, which were 132, 129, 128 and 126% greater than glyphosate applied alone (623 kg ha^{-1}), producing seed yields of 1425, 1419 and 1406 kg ha^{-1}, respectively. Aside from glyphosate alone, the three lowest yielding treatments were 2,4-D+thifensulfuron (737 kg ha^{-1}), tribenuron+thifensulfuron (826 kg ha^{-1}) and saflufenacil+thifensulfuron (796 kg ha^{-1})(Figure 3.7). 2,4-D+thifensulfuron, saflufenacil+thifensulfuron and tribenuron+thifensulfuron yielded 49%, 45% and 43% less than tribenuron+bentazon, respectively. Although the 2,4-D+imazamox+bentazon treatment resulted in the greatest soybean shoot biomass, it was one of the lowest yielding treatments, with 1194 kg ha^{-1}. However, excluding glyphosate, all treatments yielded between 737 kg ha^{-1} and 1448 kg ha^{-1}. Herbicide treatment was not significant for soybean plant height or thousand seed weight.

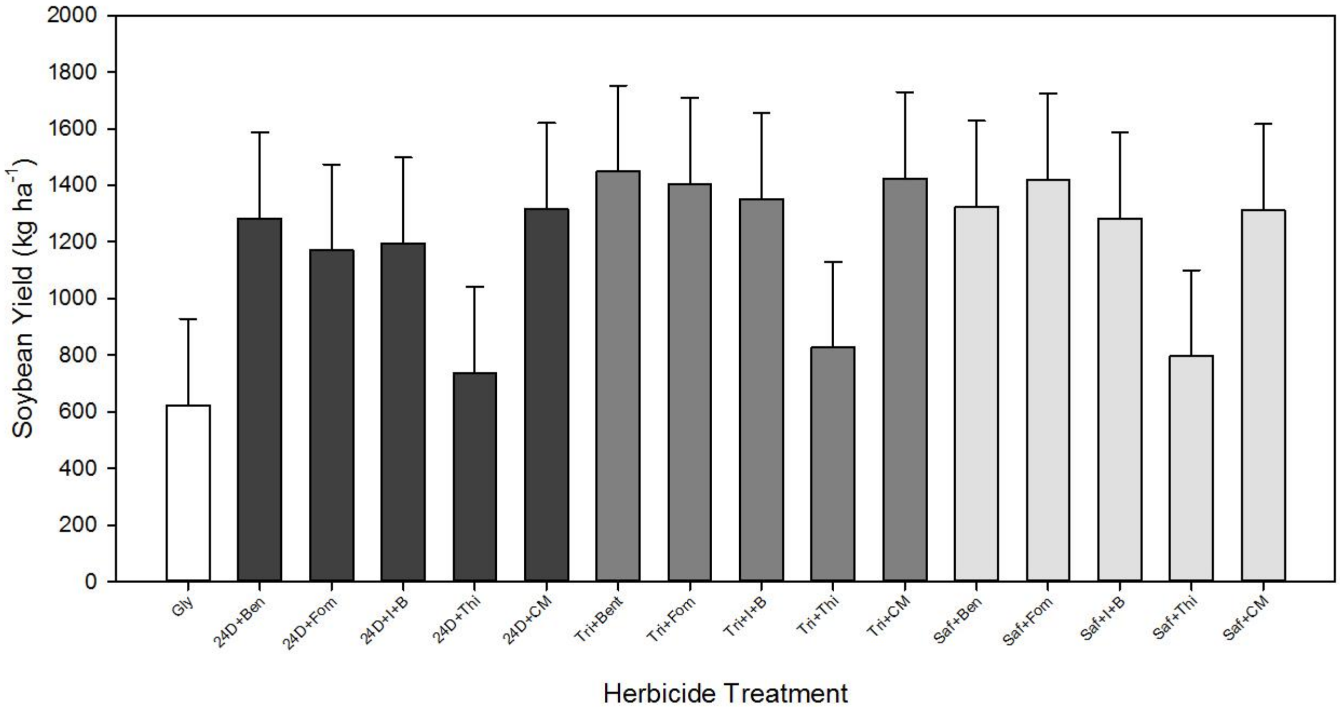

Figure 3.7. The effects of herbicide combinations on soybean yield. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

3.3.5 Volunteer Canola Shoot Biomass and Canola Seed Contamination

Significant site*treatment interactions for volunteer canola shoot biomass and seed contamination were primarily due to low volunteer canola shoot biomass values and non-significant treatment differences at Indian Head 2014 (Table 3.7). Volunteer canola shoot biomass was greatest in treatments of glyphosate alone (1548 kg ha^{-1}), which was expected as glyphosate alone will not control GR volunteer canola (Figure 3.8). Other than glyphosate alone, volunteer canola shoot biomass tended to be greatest in the treatments containing tribenuron+thifensulfuron, 2,4-D+thifensulfuron and saflufenacil+ thifensulfuron (Figure 3.8).

These treatments resulted in 303, 251 and 248 kg ha^{-1} of volunteer canola shoot biomass, respectively, and did not differ significantly from the glyphosate control.

Tribenuron+fomesafen (107 kg ha^{-1}) and 2,4-D+bentazon (92 kg ha^{-1}) also did not differ significantly from the glyphosate alone treatment. None of the remaining treatments differed significantly from each other (Appendix 1), and all generally had low levels of canola shoot biomass present, ranging from 16 to 72 kg ha^{-1}. The least canola shoot biomass was observed in treatments containing 2,4-D+imazamox+bentazon (16 kg ha^{-1}), which had 63% lower biomass than the glyphosate control. When compared to tribenuron+thifensulfuron, 2,4-D+thifensulfuron and saflufenacil+thifensulfuron, 2,4-D+imazamox+bentazon resulted in 52, 50 and 50% less canola shoot biomass, respectively (Figure 3.8).

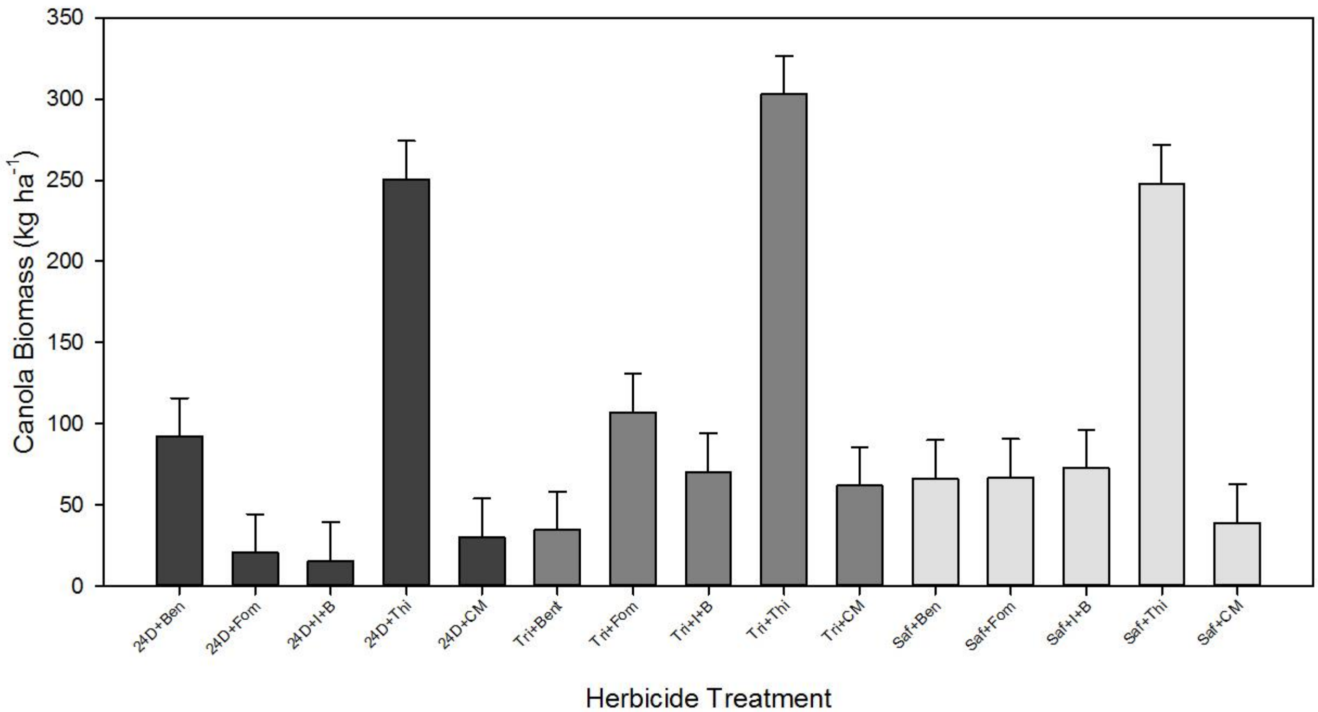

Figure 3.8. The effects of herbicide combinations on volunteer canola dry weight biomass. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1 standard error of mean.

Canola seed contamination displayed a similar trend as volunteer canola shoot biomass, in which treatments of glyphosate alone had the highest percentage of canola seed present in the harvested soybean sample (51%). This was followed by treatments containing thifensulfuron applied post-emergence (Figure 3.9), which produced contamination levels of 25-30%. None of the remaining treatments differed significantly from each other, and percentage of canola seed contamination ranged from approximately 6-12% (Appendix 1). The lowest amount of volunteer canola seed was present in the 2,4-D+imazamox+bentazon treatment (6.3%); this treatment also had the greatest soybean biomass and lowest volunteer canola shoot biomass.

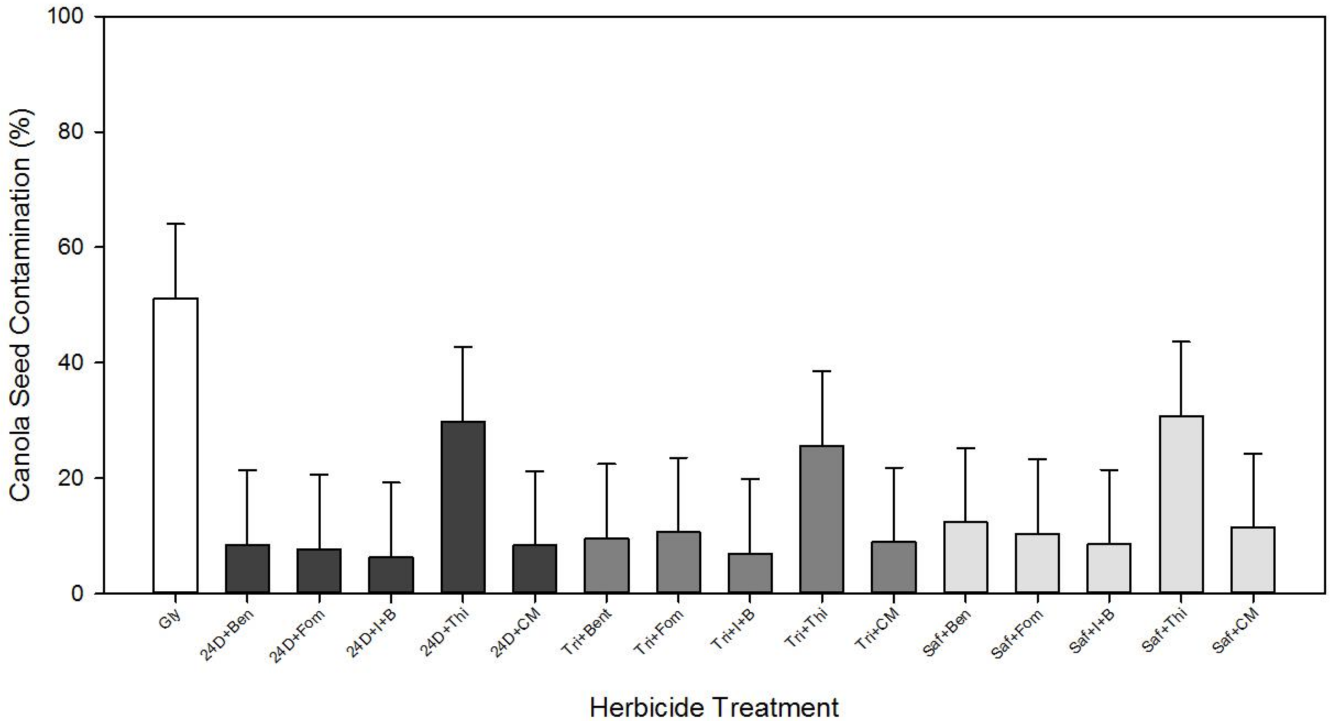

Figure 3.9. The effects of herbicide combinations on volunteer canola seed contamination. Herbicide treatments are combination treatments of pre-emergence herbicides 2,4-D, tribenuron (tri) or saflufenacil (saf) and post emergence treatments bentazon (ben), fomesafen (fom), imazamox+bentazon (I+B), thifensulfuron (thi) or cloransulam-methyl (CM). Values are derived from a combined ANOVA across site-years. Bars indicate +1standard error of mean.

3.3.6 Pre-emergence Herbicide Contrasts

Contrasts were performed to evaluate effects of the pre-emergence herbicides on several variables to determine which pre-emergence herbicide was most effective prior to the application of the post-emergence herbicides. Of the pre-emergence herbicides, saflufenacil was significantly more effective than both 2,4-D and tribenuron with respect to volunteer canola efficacy 7-10 DAT (Table 3.8). Similarly, both 2,4-D and saflufenacil had greater efficacy on canola at 21-28 DAT than tribenuron. However, none of the pre-emergence herbicides differed significantly from each other for the remaining variables (Table 3.8). Although not statistically significant, pre-emergence herbicide contrasts were marginally higher for injury ratings with 2,4-D (Table 3.8).

Table 3.8. Contrast estimates for pre-emergence herbicides for efficacy 7-10 DAT and 21-28 DAT of the pre-emergence treatment, phytotoxicity (phyto) at 7-10 DAT and 21-28 DAT of the post-emergence treatment, soybean shoot biomass and yield, and volunteer canola shoot biomass.

Herbicide Treatment	Efficacy 7-10	Efficacy 21-28	Phyto 7-10	Phyto 21-28	Soybean Biomass	Soybean Yield	Canola Biomass
2,4-D vs Tribenuron	-3.74	7.29**	4.74	4.87	-295.73	-141.11	-22.02
2,4-D vs Saflufenacil	-22.02***	1.39	3.6	4.14	-188.20	-80.38	-13.49
Tribenuron vs Saflufenacil	-18.29***	-5.9*	-1.14	-0.73	107.53	60.73	1.57

*, **,*** , significant at the 0.05, 0.01, and 0.001 probability levels.

3.4 Economic Analysis

An economic analysis was done to evaluate costs of each herbicide combination. Table 3.9 summarizes the rate and cost per hectare of each individual product used in the experiment, while Table 3.10 displays total cost of each treatment combination.

Table 3.9. Herbicide prices and application rates per hectare for each pre- and post-emergence product used in the experiment.

Herbicide	Recommended Rate (per ha)	Cost ($/ha)
2,4-D LV700 ester	444 mL	6.59
Saflufenacil	26 g	8.60
Tribenuron	15 g	9.02
Bentazon	2 L	58.19
Cloransulam-methyl	20 g	33.47
Fomesafen	1 L	44.76
Imazamox+bentazon	1 L	42.68
Thifensulfuron	10 g	35.72

When comparing total costs of combination treatments, the most expensive herbicide combinations are treatments containing bentazon post-emergence, which costs around $65 to $67 per hectare (Table 3.10). This is followed by treatments containing fomesafen or imazamox+bentazon post-emergence, which range from around $49 to $53 per hectare. The most inexpensive treatment combinations are treatments with thifensulfuron or cloransulam-methyl post-emergence, which range in cost from $40 to $43 per hectare (Table 3.10).

Table 3.10. Total cost per hectare for each herbicide treatment combination, from most expensive to least expensive.

Pre-emergent Herbicide	Post-emergent Herbicide	Total Cost ($/ha)
Tribenuron	Bentazon	67.21
Saflufenacil	Bentazon	66.79
2,4-D	Bentazon	64.79
Tribenuron	Fomesafen	53.77
Saflufenacil	Fomesafen	53.35
Tribenuron	Imazamox+bentazon	51.70
2,4-D	Fomesafen	51.35
Saflufenacil	Imazamox+bentazon	51.28
2,4-D	Imazamox+bentazon	49.28
Tribenuron	Thifensulfuron	44.73
Saflufenacil	Thifensulfuron	44.31
Tribenuron	Cloransulam-methyl	42.48
2,4-D	Thifensulfuron	42.31
Saflufenacil	Cloransulam-methyl	42.06
2,4-D	Cloransulam-methyl	40.06

There is a large variation in contribution margin between herbicide treatments. The highest contribution margin was observed with treatments of tribenuron+cloransulam-methyl, followed by saflufenacil+fomesafen and tribenuron+bentazon (Table 3.11). These treatments resulted in a contribution margin of approximately $585, $571 and $570 per hectare, respectively (Table 3.11). The lowest contribution margins occur with all treatments containing thifensulfuron post-emergence, with 2,4-D+ thifensulfuron having the lowest contribution margin of $282 per hectare. Tribenuron+thifensulfuron and saflufenacil+thifensulfuron resulted in contribution margins of $319 and $306 per hectare, respectively. The six treatments with the lowest contribution margins were all treatments that contained either 2,4-D pre-emergence or thifensulfuron post-emergence, and contribution margins ranged from $282 to $500 per hectare for these treatments.

Treatments containing tribenuron pre-emergence tended to have the highest contribution margins ($543 to $585 per hectare), with the exception of tribenuron+thifensulfuron. Treatments containing saflufenacil pre-emergence tended to be intermediate, with contribution margins of $513 to $535 per hectare, (Table 3.11).

Contribution margin tended to be more sensitive to soybean yield than herbicide cost. For example, tribenuron+bentazon had the highest herbicide cost of all treatments, but had the third highest contribution margin due to high yield (Table 3.11). Also, 2,4-D+thifensulfuron had the third lowest herbicide cost, but had the lowest contribution margin of all treatments due to very low soybean yield. In general, contribution margin tended to follow the same trend as soybean yield, with contribution margin decreasing as soybean yield decreased (Table 3.11).

Table 3.11. Gross income and contribution margin based on soybean yield for each herbicide treatment, from highest net return to lowest contribution margin.

Pre-emergent Herbicide	Post-emergent Herbicide	Soybean Yield (kg ha^{-1})	Market Price ($/kg)	Herbicide Cost ($/ha)	Gross Income ($/ha)	Contribution Margin ($/ha)
Tribenuron	Cloransulam-methyl	1425	0.44	42.48	627.00	584.52
Saflufenacil	Fomesafen	1419	0.44	53.35	624.36	571.01
Tribenuron	Bentazon	1448	0.44	67.21	637.12	569.91
Tribenuron	Fomesafen	1406	0.44	53.77	618.64	564.87
Tribenuron	Imazamox+bentazon	1351	0.44	51.70	594.44	542.74
2,4-D	Cloransulam-methyl	1315	0.44	40.06	578.60	538.54
Saflufenacil	Cloransulam-methyl	1312	0.44	42.06	577.28	535.22
Saflufenacil	Bentazon	1323	0.44	66.79	582.12	515.33
Saflufenacil	Imazamox+bentazon	1282	0.44	51.28	564.08	512.80
2,4-D	Bentazon	1283	0.44	64.79	564.52	499.73
2,4-D	Imazamox+bentazon	1194	0.44	49.28	525.36	476.08
2,4-D	Fomesafen	1170	0.44	51.35	514.80	463.45
Tribenuron	Thifensulfuron	826	0.44	44.73	363.44	318.71
Saflufenacil	Thifensulfuron	796	0.44	44.31	350.24	305.93
2,4-D	Thifensulfuron	737	0.44	42.31	324.28	281.97

3.5 Discussion

The results of this study indicate that there were significant differences between the herbicide combinations studied. Some of the herbicide treatments studied represent potential options for producers in western Canada to control volunteer GR canola in GR soybean. Differences between treatments were observed both in regard to crop safety and the control of volunteer canola. For example, fomesafen applied post-emergence resulted in high efficacy 7-10 DAT, which was likely due to rapid bleaching and desiccation characteristic of Group 14 herbicides (Duke et al. 1991). However, by 21-28 DAT, efficacy increased in treatments containing Group 2 products including thifensulfuron, cloransulam-methyl and imazamox+bentazon, while efficacy in treatments containing fomesafen and bentazon decreased. Group 2 herbicides inhibit amino acid synthesis and thus have slower herbicidal activity that takes several days to develop (Kansas State University, 2015). Many ALS inhibiting herbicides can also control weeds throughout the growing season (Beckie and Tardif, 2012).

Although efficacy of all treatments generally ranged from weed suppression to control, treatments containing thifensulfuron tended to have the lowest efficacy. This suggests that thifensulfuron provides poor control of volunteer canola, even at the high rate that was applied in error; had the correct (lower) rate been used, efficacy probably would have been even lower. Lower efficacy on volunteer canola with treatments of thifensulfuron could have been caused by the growth stage of volunteer canola at the time of application. Pageau and Lajeunesse (2008) reported that thifensulfuron efficacy on volunteer canola was reduced when applied at more advanced crop growth stages. In our study, volunteer canola at the time of herbicide application ranged in stage from cotyledon to early flowering and thus, thifensulfuron may have been less effective than the other herbicides.

Thifensulfuron treatments also tended to provide the highest crop injury following application, likely due to the high rate used in the study. It is known that thifensulfuron has a high potential of injuring soybean when applied at 4.4 to 8.8 g ha^{-1} under certain environmental conditions, such as minimal precipitation prior to herbicide application (Hart and Roskamp, 1998), and soybean is less tolerant to thifensulfuron compared with cereal crops (Ahrens, 1990). Although crop injury in our study was probably not representative of typical crop injury due to the incorrect rate we applied, thifensulfuron was also generally less effective at controlling volunteer canola than other treatments. Therefore, thifensulfuron is probably not one of the best post-emergence herbicides for controlling GR volunteer canola in GR soybean compared to other herbicides evaluated in this study.

Fomesafen also caused crop injury at 7-10 DAT above the 10% threshold limit for crops, but injury levels dropped below 10% by 21-28 DAT. This suggests that soybean is able to recover quite rapidly from damage caused by fomesafen, likely because fomesafen is a contact herbicide with very little soil activity and translocation (University of Minnesota, 1999). The crop injury symptoms that we observed from applications of fomesafen are consistent with other studies such as Johnson et al. (2002), who reported that fomesafen caused bronzing and spotting of soybean leaves when applied post-emergence. Because injury ratings associated with fomesafen were above the 10% threshold soon after application, fomesafen is not a good post-emergence option for GR soybean in western Canada. Fomesafen is also persistent in soil, and has a half-life of approximately 100 days (Ontario Ministry of Agriculture, Food and Rural Affairs, 2013). This is an extended period of time compared to other products used such as cloransulam-methyl and thifensulfuron, which have half-lives of approximately 8-33 and 12 days, respectively (Shaner, 2014). Fomesafen is only registered for use in the Red River Valley of Manitoba because of concerns around soil persistence in the drier soils of Saskatchewan. Differences in soil texture and organic matter, precipitation and environmental conditions between Saskatchewan and the Red River Valley of Manitoba may account for why fomesafen caused unacceptable injury in this experiment. For example, soil test results determined that Carman, MB had predominantly sandy soil with 54% sand, 15% silt and 31% clay with 6% organic matter content (Table 3.1). Conversely, Saskatoon had predominantly clay soil, with 19% sand, 36% silt and 45% clay and 2.4% organic matter. Cobucci et al. (1998) found that fomesafen has much higher mobility in sandy textured soils, such as Carman, and therefore less persistence. Also, soil persistence of fomesafen is greater in soil with higher clay contents due to greater herbicide adsorption. Carman also generally receives higher precipitation, with a long-term normal of 368 mm, compared to Saskatoon's long-term normal of 236 mm. Fomesafen tends to be less persistent in wet soils compared to dry soils, due to lower herbicide adsorption (Cobucci et al. 1998).

Bentazon, fomesafen, imazamox+bentazon and cloransulam-methyl all had higher crop injury ratings at both 7-10 DAT and 21-28 DAT when combined with 2,4-D ester compared with tribenuron or saflufenacil. This indicates that 2,4-D likely caused some injury, regardless of which post-emergence herbicide was applied to soybean. The 2,4-D label requires a minimum of seven days between application and soybean planting (Saskatchewan Ministry of Agriculture, 2016), and a span of only three to five days had passed in 2014. When the experiment was repeated in 2015, a period of seven days had elapsed between 2,4-D application and soybean planting, but some crop injury still occurred. These results are consistent with Thompson et al. (2007), who reported that 2,4-D ester injured soybean up to 11% when applied seven days before planting, and up to 18% when applied immediately before seeding. However, when the planting interval was increased to 21 days, crop injury was nearly zero in that study. Our results show that 2,4-D has potential for soybean crop injury in some environments and is therefore not an optimal pre-emergence product for GR soybean (if a seven day planting interval is used). Crop injury following 2,4-D application is likely dependent on soil and environmental conditions. 2,4-D has been shown to degrade slower in soils with low organic matter, low microbial biomass and low pH (Voos and Groffman, 1997; Kah et al. 2007). All of the site-years in Saskatchewan had relatively low organic matter content, ranging from 2.4% to 3.5%, with Carman having 6%. 2,4-D degradation also tends to be slower in cold, dry soils, while warm soils with adequate moisture tend to degrade 2,4-D faster (Foster and McKercher, 1973; Johnson et al. 1995). In 2014, the average temperature was lower at all sites than the long-term average, and precipitation was lower at most sites. Cold, dry soils and low organic matter content at most sites likely slowed the degradation of 2,4-D and may have contributed to crop injury. Nevertheless, 2,4-D may be an acceptable product for western Canada if the interval between application and crop planting is increased, possibly to around 14 days.

Volunteer canola seed contamination is a significant issue as it may cause dockage, thereby reducing the grade of soybean, as well as contributing to seedbank replenishment. Each canola seed in the seedbank will result in either persistence, successful germination and emergence, or death (Gulden et al. 2003a). Volunteer canola can persist in low densities in soil four to five years after production (Simard et al. 2002). We found that treatments of glyphosate alone resulted in canola seed contamination of 51%, which would very effectively replenish the seed bank. In contrast, most of the other herbicide treatments resulted in low levels of volunteer canola seed contamination (6-12%). It is evident that effective control of volunteer canola in soybean is critical not only to avoid soybean yield losses and contamination, but also to reduce canola seedbank inputs.

Promising pre+post tank mixtures for western soybean producers that were identified in this study include tribenuron+bentazon, tribenuron+imazamox+bentazon, tribenuron+cloransulam-methyl, saflufenacil+bentazon, saflufenacil+imazamox+bentazon and saflufenacil+cloransulam-methyl. Based on herbicide cost alone, the most cost-effective options for producers are tribenuron+cloransulam-methyl or saflufenacil+cloransulam-methyl, as both of these combinations cost approximately $42 per hectare, while tribenuron+imazamox+bentazon and saflufenacil+imazamox+bentazon cost approximately $51 and $52 per hectare, respectively. Although tribenuron+bentazon was the highest yielding treatment, its cost was significantly higher at $67 per hectare; however this treatment had the third highest contribution margin, despite high herbicide costs (Table 3.11).

Contribution margins should also be taken into consideration, along with herbicide costs. The highest contribution margin was observed with the treatment of tribenuron+cloransulam-methyl, as this treatment had a relatively low herbicide cost and the second greatest soybean seed yield. Although saflufenacil+fomesafen and tribenuron+fomesafen produced the second and fourth highest contribution margins, respectively, fomesafen caused unacceptable crop injury at 7-10 DAT, although crop injury did not translate into significant yield loss. Based on the economic analysis, the best herbicide combination for producers is tribenuron+cloransulam-methyl, followed by tribenuron+bentazon and tribenuron+imazamox+bentazon treatments. Of these three options, tribenuron+imazamox+ bentazon had the lowest amount of volunteer canola seed contamination at 6.9%, compared to tribenuron+cloransulam-methyl and tribenuron+bentazon, which had contamination levels of 8.9% and 9.5%, respectively.

3.6 Conclusion

Volunteer canola control generally ranged from suppression to control across most herbicide treatments, but thifensulfuron treatments had the greatest amount of volunteer canola shoot biomass present following application. Fomesafen was effective, but at 7-10 DAT of the post-emergent treatment, the phytotoxicity ratings were above the acceptable threshold. Some injury due to 2,4-D treatments was also observed and therefore, 2,4-D is not optimal when a 7 day or less planting interval is used. Tribenuron+bentazon, tribenuron+imazamox+bentazon, tribenuron+cloransulam-methyl, saflufenacil+bentazon, saflufenacil+imazamox+bentazon and saflufenacil+cloransulam-methyl all provided good control of volunteer canola and low crop injury, with similar seed yield results. However, the highest net return was observed in the tribenuron+cloransulam-methyl treatment. Unfortunately, cloransulam-methyl is currently only registered for use in eastern Canada and cannot be used in western Canada at this time. Considering this, the next most efficacious and economical options for producers would be tribenuron+bentazon and tribenuron+imazamox+bentazon, both of which are currently registered for use in western Canada.

4.0 Evaluating planting date and seeding rate for management of glyphosate resistant volunteer canola in glyphosate resistant soybean

4.1 Introduction

Cultural weed management techniques can have a substantial effect on crop competitiveness, as well as crop productivity. One important method of cultural weed management is optimal seeding rate. Soybean is generally a poor competitor with weeds; however seeding rate can improve crop competitiveness due to both increased plant stand, as well as more rapid canopy development (Blackshaw et al. 2002; Guillermo et al. 2009).

The recommended seeding rate for soybean in Saskatchewan is approximately 493,000 to 630,000 seeds ha^{-1} (44 to 57 plants m^{-2}) (Saskatchewan Pulse Growers, 2017). Several studies have found that increasing soybean seeding rate has a significant effect on reducing weed populations and improving crop competition (McWhorter and Barrentine, 1975; Nice et al. 2001; Norsworthy and Oliver, 2001; Guillermo et al. 2009). Several studies also have reported a yield increase in soybean with higher seeding rates, largely due to improved weed control, light interception, and rapid canopy development (Elmore, 1998; Place et al. 2009; Cox and Cherney, 2011). However, these studies also report an asymptotic response to seeding rate, where yields reach a plateau or decline; this is known as the law of constant final yield (Weiner and Freckleton, 2010). High seeding rates also can pose agronomic challenges, as increased plant density increases intraspecific competition for resources, as well as increases potential for disease (Pennypacker and Risius, 1999; Krupinsky et al. 2002).

Planting date can also have a sizeable impact on crop yield and competitiveness with weeds, although studies have shown inconsistent results with regard to competitiveness. Some studies have found that soybean has a higher competitive ability with weeds when planted early (Klingaman and Oliver, 1994), yet others have reported soybean to be more competitive with weeds with delayed planting (Rushing and Oliver, 1998; Liebman et al., 2001; Coulter and Nafziger, 2007). The effects of planting date on soybean yield are also inconsistent. Delaying planting has been shown to significantly reduce soybean yield (Hardman and Gonsolus, 1994; De Bruin and Pederson, 2008b; Robinson et al. 2009), while other studies have reported yield increases with late soybean planting (Buhler and Gunsolus, 1996; Rushing and Oliver, 1998). These differences in crop competitiveness and soybean yield response to seeding date are due to many factors such as weed species present, weed emergence timing, time of weed removal, and environmental conditions. Nevertheless, studies have found that integrating various seeding rates and planting dates can maximize productivity and significantly improve soybean's competitiveness (De Bruin and Pederson, 2008b; Lee et al. 2008).

A major weed of soybean in western Canada is volunteer canola, which is an early emerging species (Lawson et al. 2006). Dicot weeds, such as volunteer canola, tend to cause greater yield loss in soybean compared to monocots (Nave and Wax, 1971). Volunteer glyphosate-resistant (GR) canola poses a challenge to producers growing GR soybean because of limited herbicide options for control. In addition, volunteer canola is very competitive and can persistent in the seedbank. By coupling cultural control methods with the results presented in Chapter 3, an integrated weed management (IWM) approach could be developed that does not rely on herbicides alone. IWM in soybean consisting of mechanical weed control methods combined with banded herbicide application have been shown to have no difference in weed density or crop yield compared to conventional weed control using only broadcast herbicide (Swanton et al. 2002). There is great potential for IWM in soybean crops to reduce the reliance on herbicides alone by combining herbicide use with optimal seeding rate and seeding date. Therefore, the present study was conducted to evaluate the effects of seeding rate and seeding date on soybean and its competitiveness with GR volunteer canola, and to determine the optimal seeding rate and seeding date for soybean in western Canada when competing with volunteer canola. The hypothesis of this study was that soybean competition with volunteer canola would be significantly improved with higher seeding rates and a mid-May seeding date.

4.2 Materials and Methods

4.2.1 Site Description

Field experiments were conducted in 2014 and 2015 at the Kernen Crop Research farm (52°15' N, 106°53' W) at Saskatoon, SK, at the Western Applied Research Corporation (52°21' N, 108°49' W) in Scott, SK, at the Indian Head Agricultural Research Foundation (50°31' N, 103°39' W) research farm at Indian Head, SK, and at the University of Manitoba Research farm (49°30' N, 98°00' W) at Carman, MB. Saskatoon and Scott are located on a Dark Brown soil, while Indian Head and Carman are located on Black soils. Soil descriptions are presented in Table 3.1 (Chapter 3).

4.2.2 Experimental Procedures

The experimental design was a split-plot with 15 treatments and four replications. Main plots were seeding date (early, intermediate and late) and sub plots were seeding rates (targeted 10, 20, 40, 80 and 160 plants m^{-2} corresponding to 101,880, 203,775, 407,550, 815,100 and 1,630,200 seeds ha^{-1}). Plots were seeded in late May, early June and mid-June in 2014 and mid-May, late May and early June in 2015. Actual seeding dates are presented in Table 4.1. Seeding dates in 2014 were later than targeted due to environmental conditions, which delayed seeding.

Each subplot at Saskatoon and Scott measured 2 m wide x 6 m long, while subplots at Indian Head were 2.7 m wide x 10.7 m long, and subplots at Carman were 2.5 m wide x 8 m long. Main plots at Saskatoon and Scott measured 10 m wide x 6 m long, while main plots at Indian Head were 13.5 m wide x 10.7 m long, and plots at Carman were 12.5 m wide x 8 m long. Border plots were seeded at all sites to minimize border effects. Soil samples were taken in the fall at depths of 0-15, 15-30 and 30-60 centimeters to determine nutrient levels in the soil, as well as soil pH and organic matter. No fertilizer was added as soybean fixes its own nitrogen, and phosphorous levels in the soil were adequate at time of sampling. All plots received a 450 g ae ha^{-1} application of glyphosate immediately after seeding to control emerged weeds.

The soybean cultivar used was P001T34R, and it was pre-treated with Cruiser Maxx Vibrance Beans®, a co-pack of Cruiser Maxx Beans (thiamethoxam+ +fludioxonil+metalaxyl) and Vibrance 500 FS (sedaxane) applied at rates of 195 mL + 10 mL 100 kg^{-1} of seed, respectively. Soybean seed was pre-inoculated with Optimize® inoculant (*Bradyrhizobium japonicum)*, and granular TagTeam (*Pencillium bilaii*) was applied at a rate of 3 kg ha^{-1} at the time of seeding. Soybean was seeded at a 3 cm depth with a cone seeder equipped with disc openers spaced at 40 cm at Saskatoon, while hoe openers were used at the other locations. A soybean survival rate of 75% (Ontario Ministry of Agriculture, Food and Rural Affairs, 2009) was used to determine seeding rates; therefore actual seeding rates were 16, 27, 53, 106 and 215 seeds m^{-2}. Actual seeding dates and cumulative growing degree days (base temperature 10 C, Zhang et al. 2001) for each seeding date are presented in Table 4.1. Volunteer canola was seeded at a rate of 80 seeds m^{-2} using a 50% survival rate (Canola Council of Canada, 2015) to establish a target plant density of 40 plants m^{-2}. Canola was cross-seeded with a plot drill across the entire trial immediately following each soybean seeding date. The canola variety used was Dekalb 72-

65 RR pre-treated with Acceleron® (difenoconazole+metalaxyl+fludioxonil+ thiamethoxam+*bacillus subtilis*) at 160 mL Acceleron DX-910 + 1.5L Helix Xtra/100 kg of seed.

Table 4.1. Seeding dates and growing degree days for seeding date treatments at Saskatoon, Scott and Indian Head, SK and Carman, MB in 2014 and 2015.

Site-year	Seeding Date Treatment	Seeding Date	Growing Degree Days (GDD)
Saskatoon 2014	Mid May	May 22	15.7
	Late May	June 1	72.7
	Early June	June 9	85.5
Indian Head 2014	Mid May	May 30	72.1
	Late May	June 10	111.4
	Early June	Missing	NA
Carman 2014	Mid May	May 23	5.6
	Late May	May 29	59.6
	Early June	June 11	160.2
Saskatoon 2015	Mid May	May 13	21.2
	Late May	May 26	75.6
	Early June	June 5	88.9
Scott 2015	Mid May	May 15	10.7
	Late May	May 26	37.1
	Early June	June 5	71.7
Indian Head 2015	Mid May	May 19	23.7
	Late May	May 28	74.8
	Early June	June 10	134.4
Carman 2015	Mid May	May 26	65.6
	Late May	June 11	156.5
	Early June	June 23	235.6

Soybean density was assessed by counting plants in the front, middle and back of each plot in two, 1-m rows two weeks after emergence. Volunteer canola stand density was also evaluated two weeks after emergence in three randomly placed 0.5 m^2 quadrats per plot. Crop and volunteer canola biomass sampling was conducted at the canola podding stage. Aboveground shoot biomass samples were collected in two 0.5 m^2 quadrats per plot from the front and back of each plot. Samples were cut above just above the ground surface, with the canola and soybean separated and placed in brown paper bags. All material was oven dried at 80°C for 72 hours and weighed. Soybean crop height was measured just prior to biomass sampling by measuring the distance from the ground to the top of the plant on 5-10 plants per plot.

Plots were harvested with a small plot combine and samples were dried, cleaned, and weighed to determine final yield. Soybean is considered dry at 14% moisture content and therefore, yields were adjusted to 14% moisture content. Thousand seed weight was determined by weighing 250 soybean seeds and multiplying by four. Volunteer canola seeds that were cleaned out of soybean samples were also weighed to determine volunteer canola seed contamination. Volunteer canola seed contamination is presented as kg ha^{-1} in the harvested soybean sample

4.2.3 Statistical Analysis

Residuals were initially tested to ensure that the assumptions of ANOVA were met. The Shapiro-Wilk test in PROC UNIVARIATE was used to assess normality and the Levene's test was used to test for homogeneity of variance. Where there was heterogeneity between sites, the REPEATED statement was used to account for this heterogeneity. If model fit was improved by modeling heterogeneity, then this model was used. Where model fit was not improved, the original PROC MIXED model was used.

Data were analyzed with the PROC MIXED procedure in SAS 9.3. Rate, date and rate*date treatments were considered fixed effects in the model, while random effects consisted of site, block, and site interactions with fixed effects. To assess the significance of random effects and their interactions with fixed effects, covariance parameters were examined using the COVTEST option of PROC MIXED in SAS 9.3 to determine if the site-years could be combined and if conclusions could be drawn from a broader (population-based) inference space (SAS Institute 2014).

Orthogonal polynomial contrasts were calculated to determine whether variables had a linear or quadratic response to seeding rate. Analysis of covariance (ANCOVA) was used to calculate linear or quadratic regression coefficients for seeding rate responses (Yang and Juskiw, 2011). Contrasts were used to determine if regression coefficients were significantly different between sites. Sites with similar regression coefficients were combined for analysis.

4.2.3.1 Economic Analysis

An economic analysis was conducted wherein the soybean market price was $0.44 per kilogram ($11.85 per bushel), which is an average number based on the market price projection for 2016 of $0.39 per kilogram (Saskatchewan Crop Insurance Corporation, 2016), current market price of $0.42 (Rayglen Commodities, 2016) and average market price of $0.49 from 2013, 2014 and 2015 (Agriculture and Agri-Food Canada, 2016). Based on the recommended seeding rate of 40 plants m^{-2}, the average soybean seed cost is $233.17 per hectare for seed and seed treatment (Government of Manitoba, 2016). Gross income was calculated by multiplying soybean seed yield by market price. A contribution margin was calculated by subtracting the seed cost from the gross income. Differences in soybean yield and volunteer canola shoot biomass were determined by comparing each seeding rate to the standard rate of 40 plants m^{-2}.

4.3 Results

Data from Scott in 2014 were omitted from analysis due to missing data and errors in experimental design. In addition, the Indian Head site was unable to plant the last seeding date in 2014 due to flooding and therefore, data from this site only includes two seeding dates. Environmental conditions are described in Chapter 3 (Table 3.5). P-values derived from analysis of variance are shown in Table 4.2.

Table 4.2. ANOVA results (P-values) for soybean density, plant height, shoot biomass, seed yield, thousand seed weight, canola shoot biomass, and seed contamination (SC); as well as p-values for variable relationship with seeding rate. P-values for random effects (site-year and site-year by treatment interactions) were assessed using the Wald Z Test (COVTEST).

		Soybean				Canola	
Source	Density	Height	Biomass	Yield	TSW	Biomass	SC
Rate	<.0001***	<.0001***	<.0001***	<.0001***	0.09	<.0001***	0.0012**
Date	0.1752	0.0909	0.6321	0.9519	0.1757	0.5445	0.3341
Date*Rate	0.0855	0.1328	0.6499	0.9835	0.9185	0.852	0.7346
Site-year	0.2588	0.0795	0.1141	0.4114	0.0581	0.0733	0.1849
Site*Rate	0.1109	0.1723	0.0105*	0.009**	0.0895	0.023*	0.0138*
Site*Date	0.0838	0.014*	0.016*	0.0156*	0.0411*	0.0251*	0.0694
Site*Date*Rate	0.0059**	0.2948	0.0071**	0.0023**	0.0271*	0.2186	0.6752
Rate Linear	<.0001***	<.0001***	<.0001***	<.0001***	0.0067**	<.0001***	<.0001***
Rate Quadratic	0.7866	0.2418	0.0211*	0.0324*	0.6365	0.2625	0.3201

*,**,***, significant at the 0.05, 0.01 and 0.001 probability levels. NA denotes not applicable.

4.3.1 Seeding Rate and Seeding Date Effects on Soybean

Soybean Density

Seeding rate had a significant effect on soybean density (P<.0001) (Table 4.2). Density increased linearly with increasing seeding rates, although percent emergence actually decreased with increasing seeding rates. Seeding rates of 16, 27, 53, 106 and 215 seeds m^{-2} resulted in approximately 100, 74, 64, 56 and 50% of sown seed producing viable plants, respectively (data not shown). Although seeding date and site were not statistically significant in the combined analysis (Table 4.2), there was a significant site*rate*date interaction for soybean density.

When analyzed within site-year, three of the site-years (Carman 2015, Saskatoon 2015 and Scott 2015) had no date*rate interaction and seeding date was not significant. The remaining four site-years (Saskatoon 2014, Indian Head 2014, Carman 2014 and Indian Head 2015) had significant rate*date interactions; seeding rate response to seeding date tended to be variable at these site-years. The greatest percentage emergence was observed in the late seeding date at both Carman 2014 and Indian Head 2015 (Figure 4.1). For example, at a target plant density of 40 plants m^{-2} at Indian Head 2015, soybean emergence was 49, 47 and 70% at the early, intermediate and late seeding date, respectively. Conversely, the greatest percentage emergence was observed at the early seeding date at the other site-years (Saskatoon 2014, Indian Head 2014; Figure 4.1).

Density data were combined across the Carman, Saskatoon, and Scott sites in 2015, as there were no site*date interactions, and regression coefficients did not differ significantly. In all cases, plant density exhibited a linear increase as seeding rate increased, with the incremental increases ranging from 0.36 to 1.3 plants m^{-2} for every unit increase in seeding rate. Differences

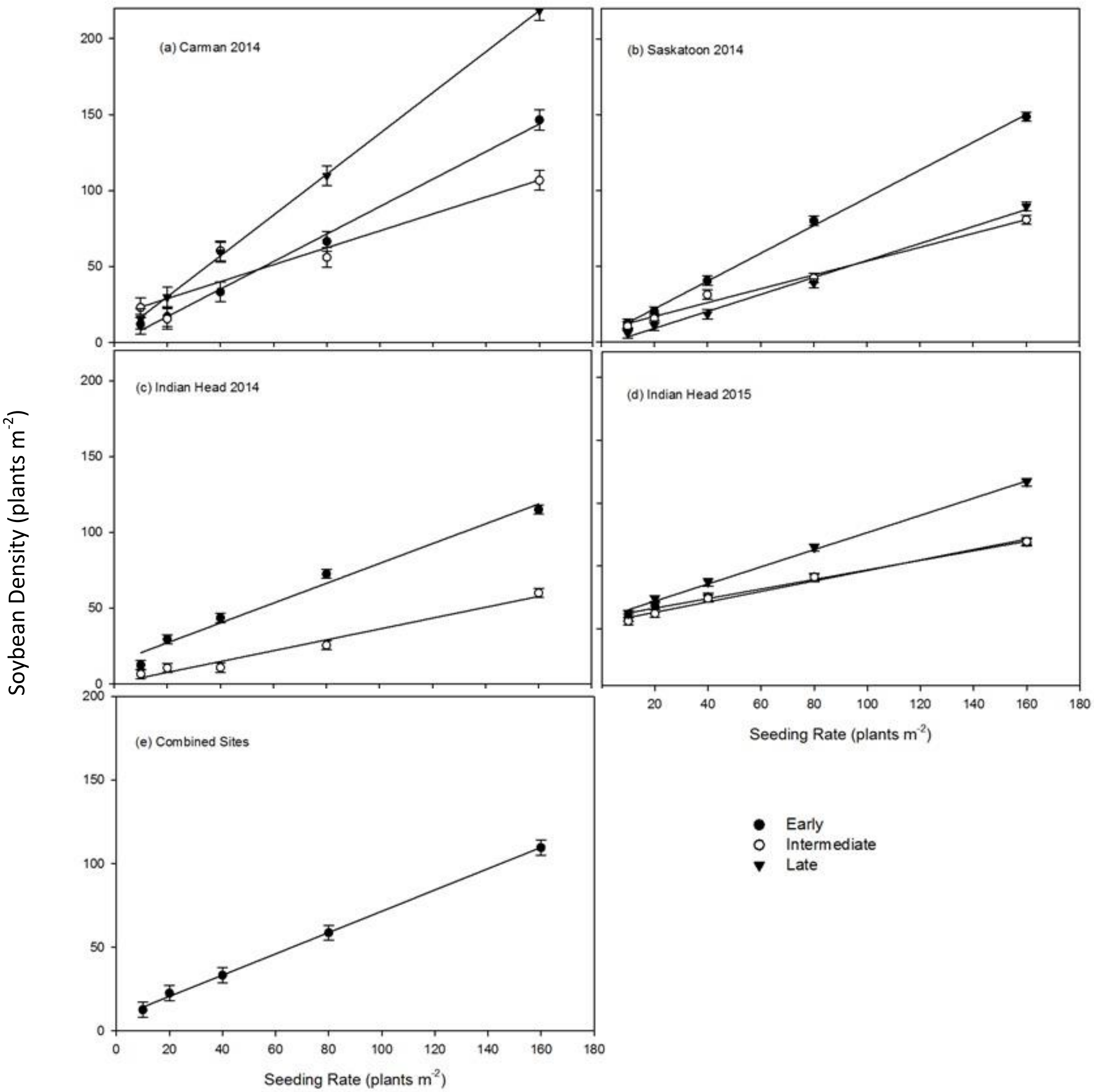

Figure 4.1. Effect of seeding rate and seeding date on soybean density at site years where there were site*date*rate interactions (a-d); and Carman 2015, Saskatoon 2015 and Scott 2015 combined, where there were no site*date*rate interactions (e). Bars indicate +/-1 SEM. **Line equations for seeding dates: (a)** Early: $y = 0.9062x - 1.1354$. $R^2 = 0.9959$. Intermediate: $y = 0.5576x + 17.729$. $R^2 = 0.8805$. Late: $y = 1.3461x + 3.0938$. $R^2 = 0.9997$. **(b)** Early: $y = 0.9166x + 3.5208$. $R^2 = 0.9988$. Intermediate: $y = 0.5598x -2.1563$. $R^2 = 0.9935$. Late: $y = 0.4563x + 7.7604$. $R^2 = 0.9883$. **(c)** Early: $y = 0.6538x + 14.063$. $R^2 = 0.9795$. Intermediate: $y = 0.3578x + 0.4688$. $R^2 = 0.9751$. **(d)** Early: $y = 0.3797x + 8.9583$. $R^2 = 0.9894$. Intermediate: $y = 0.4154x + 4.9479$. $R^2 = 0.9887$. Late: $y = 0.6816x + 8.4896$. $R^2 = 0.9973$. **(e)** $y = 0.6367x + 7.8536$. $R^2 = 0.9989$.

in the response of soybean density to seeding date are likely due to environmental conditions such as soil temperature, soil moisture, precipitation, and soil characteristics.

Soybean Plant Height

Although the main effects of seeding date and site were not significant when site-years were combined, there was a site*date interaction for soybean plant height (Table 4.2). Overall, soybean plant height exhibited a positive linear relationship with increasing seeding rate ($P<0.0001$) (Table 4.2; Figure 4.2). For example, soybean plant height increased by 9.25 % as seeding rate was increased from 10 plants m^{-2} to 160 plants m^{-2}. When plant height data were combined across site-years, plant height tended to be greater at intermediate and late seeding dates (56 and 56 cm) when compared to the early seeding dates (48 cm), although not significantly ($P=0.09$). The seeding date effect was statistically significant at Indian Head 2015, Saskatoon 2014, and Saskatoon 2015, but not at the remaining four site-years, which likely accounted for the overall site*date interaction. At the three sites where seeding date was significant, the early seeding date was shorter than the intermediate and late seeding date (Table 4.3), which is consistent with the overall trend from the combined analysis.

Table 4.3. Soybean plant height at three seeding dates at Indian Head 2015, Saskatoon 2014 and Saskatoon 2015 where height had a site*date interaction.

	Indian Head 2015 (cm)	Saskatoon 2014 (cm)	Saskatoon 2015 (cm)
Early	38.9 C	68.4 B	33.8 C
Intermediate	52.9 B	79.5 A	47.8 B
Late	61.9 A	64.1 B	57.6 A
$LSD_{0.05}$	5.6	5.5	4.8

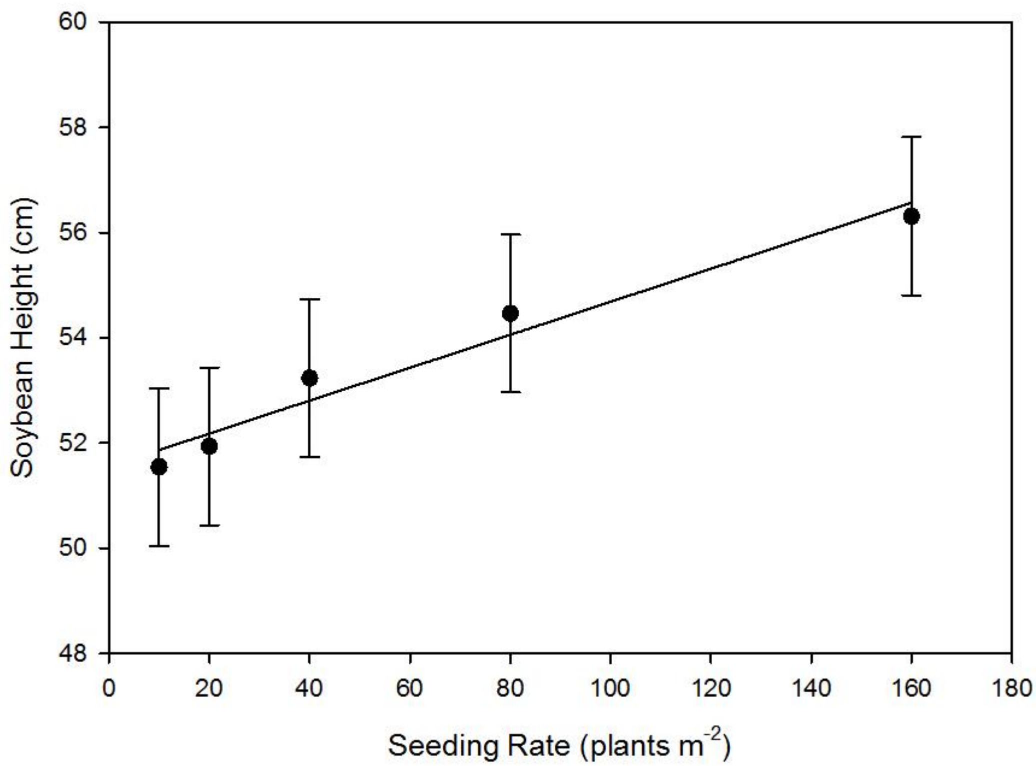

Figure 4.2. Soybean plant height response to seeding rate at 10, 20, 40, 80 and 160 plants m^{-2}. Data points represent the means of all site-years at each seeding rate. Bars indicate +/-1 SEM. Linear equation: $y = 0.0313x + 51.55$. $R^2 = 0.9622$.

Soybean Aboveground Shoot Biomass

Overall, seeding rate exhibited a quadratic relationship with soybean shoot biomass ($P<0.0001$) (Table 4.2). There was a significant site*date*rate interaction for soybean shoot biomass (Table 4.2) at three of the site-years (Indian Head 2014, Saskatoon 2014 and Saskatoon 2015). This was likely because the magnitude of the soybean shoot biomass response to seeding rate differed depending on the seeding date (Figure 4.3). At Indian Head 2014 and Saskatoon 2014, shoot biomass exhibited a greater response to seeding rate at the early seeding date compared with intermediate or late seeding dates (Figure 4.3). For example, at Indian Head 2014, a seeding rate of 40 plants m^{-2} produced a soybean shoot biomass of 400 kg ha^{-1} at the intermediate seeding date, compared to 1210 kg ha^{-1} at the early seeding date (Figure 4.3). Saskatoon 2014 had a similar trend, while at Saskatoon in 2015, shoot biomass exhibited a greater response to seeding rate at the latest seeding date compared to early or intermediate dates; however the differences were less drastic. For example, at 40 plants m^{-2}, the early, late and intermediate seeding dates resulted in soybean shoot biomass values of 1509, 1546 and 2310 kg ha^{-1}, respectively (Figure 4.3).

Four site-years exhibited only a seeding rate main effect (Figure 4.3), where soybean shoot biomass increased with increasing seeding rates consistently across seeding dates (no seed date*seed rate interaction). The regression coefficients were not significantly different for Carman 2014, Carman 2015 or Scott 2015 and thus, they were combined (Figure 4.3). Regression coefficients for Indian Head 2015 were significantly different and could not be combined with the other three site-years (Figure 4.3). Although shoot biomass consistently increased with increasing seeding rates where sites were combined, the marginal increase in shoot biomass was smaller at higher seeding rates. For example, when seeding rate increased from 20 plants m^{-2} to 40 plants m^{-2}, soybean shoot biomass increased by 65%. However, when seeding rate increased from 40 plants m^{-2} to 80 plants m^{-2} and 80 plants m^{-2} to 160 plants m^{-2}, soybean shoot biomass increased only by 38% and 34%, respectively (Figure 4.3). Similar observations were made at Indian Head in 2015 (Figure 4.3).

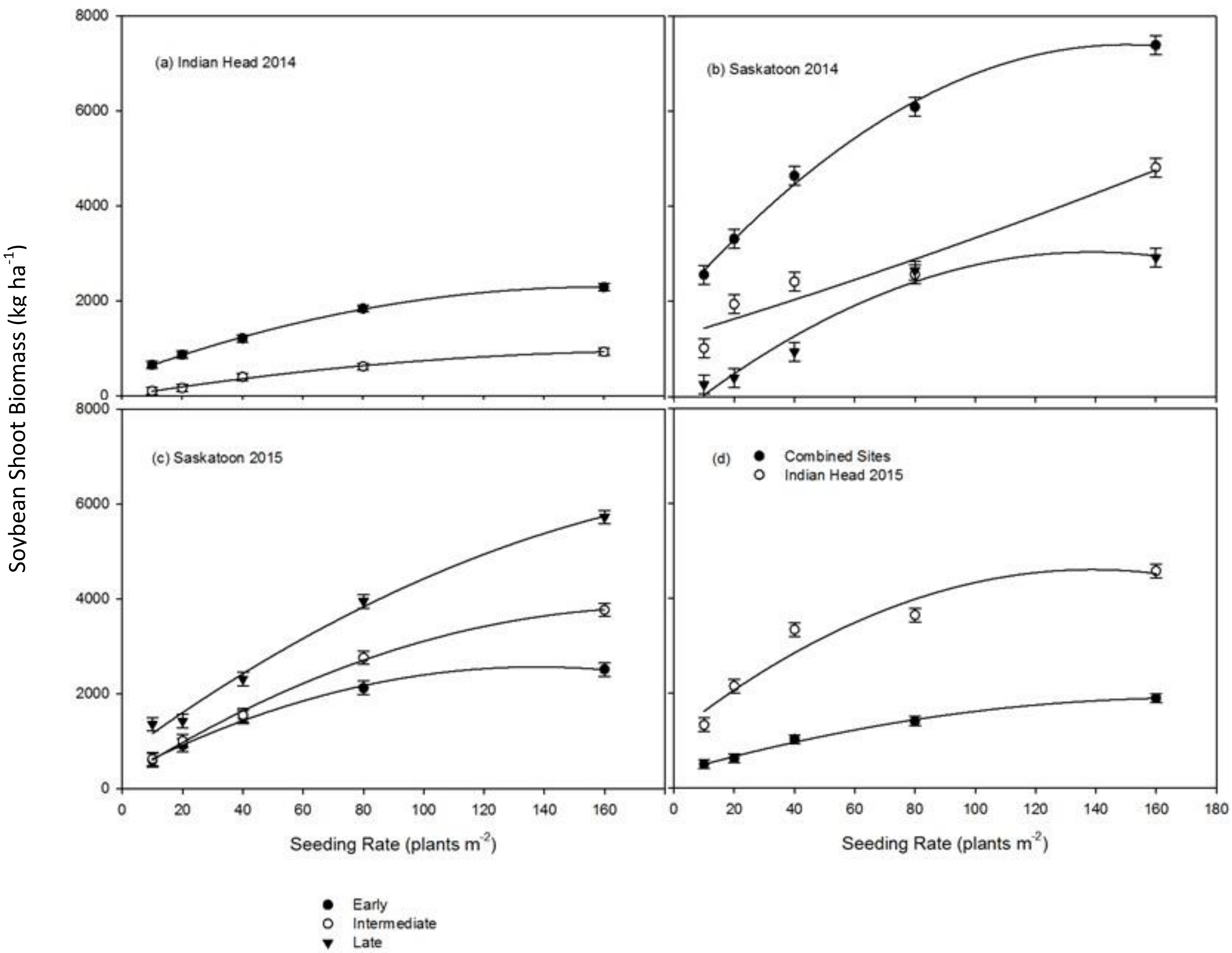

Figure 4. 3. Effect of seeding rate and seeding date on soybean shoot biomass at site years where there were site*date*rate interactions (a-c); Carman 2014, Carman 2015 and Scott 2015 combined, and Indian Head 2015, where there were no site*date*rate interactions (d). Bars indicate +/-1 SEM. **Line equations for seeding dates: (a)** Early: $y = -0.0734x^2 + 23.443x + 416.86$. $R^2 = 0.9994$. Intermediate: $y = -0.027x^2 + 10.106x - 1.6176$. $R^2 = 0.994$. **(b)** Early: $y = -0.2419x^2 + 72.637x + 1948.4$. $R^2 = 0.9966$. Intermediate: $y = 0.0183x^2 + 19.107x + 1243.5$. $R^2 = 0.9346$. Late: $y = -0.1817x^2 + 50.401x - 456.74$. $R^2 = 0.9656$. **(c)** Early: $y = -0.119x^2 + 32.728x + 312.85$. $R^2 = 0.9965$. Intermediate: $y = -0.111x^2 + 39.994x + 216.9$. $R^2 = 0.9981$. Late: $y = -0.0951x^2 + 46.673x + 706.72$. $R^2 = 0.9932$. **(d)** Combined sites: $y = -0.0523x^2 + 18.169x + 318.02$. $R^2 = 0.9951$. Indian Head 2015: $y = -0.1799x^2 + 49.929x + 1134.5$. $R^2 = 0.9318$.

Soybean Seed Yield

Soybean showed consistent seed yield increases across site-years with regard to seeding rate effects (P<0.0001), but due to significant differences between regression coefficients and site*date*rate interactions (Table 4.2), data were not combined across all site-years. When site-years were analyzed separately, five of the seven site-years had a rate*date interaction, while the remaining two (Carman 2015 and Scott 2015) had a seeding rate effect only. Of the five site-years that had a date*rate interaction, the early seeding date yielded highest at Indian Head 2014 and Saskatoon 2014 (Figure 4.4), while the late seeding date yielded highest at Carman 2014, Indian Head 2015 and Saskatoon 2015 (Figure 4.4). The rate*date interaction at these five site-years may have been due to a difference in the magnitude of the response to seeding rate at different seeding dates. For example, at Indian Head 2014 a seeding rate increase from 40 plants m^{-2} to 80 plants m^{-2} produced a soybean seed yield increase of 43% at the intermediate seeding date and 82% at the early seeding date (Figure 4.4). Similarly, soybean seed yield at Carman 2014 increased by 52, 69 and 39% at the early, intermediate and late seeding dates, respectively, when seeding rate was increased from 40 plants m^{-2} to 80 plants m^{-2}. Conversely, at Carman 2014, seed yield increased by 55, 25, and 21% at the early, intermediate and late seeding date when seeding rate was increased from 80 plants m^{-2} to 160 plants m^{-2} (Figure 4.4).

The late and intermediate seeding dates yielded highest at Indian Head 2015, with the early seeding date yielding significantly lower (Figure 4.4). The magnitude of the seed yield increase at higher seeding rates also varied with seeding date. For example, increasing seeding rate from 20 plants m^{-2} to 40 plants m^{-2} increased soybean seed yield by 30, 60 and 57% at the early, intermediate and late seeding dates, respectively. However, when seeding rates were increased from 40 plants m^{-2} to 80 plants m^{-2} and 80 plants m^{-2} to 160 plants m^{-2}, the magnitude of seed yield increase was highest at the early date in both cases (Figure 4.4).

Results at Saskatoon 2015 were similar to results at Indian Head 2015, with the late seeding date yielding highest and the early seeding date yielding significantly lower. The magnitude of the yield increase again varied with seeding date at these sites. The late seeding date had the greatest magnitude of seed yield change when seeding rate increased from 20 plants m^{-2} to 40 plants m^{-2}, as yield increased by 67, 29 and 81% at the early, intermediate and late seeding dates, respectively. By contrast, when seeding rate increased from 40 plants m^{-2} to 80 plants m^{-2}, soybean seed yield increased by 116, 117 and 82% at the early, intermediate and late seeding dates. Similar trends were observed as seeding rate increased from 80 plants m^{-2} to 160 plants m^{-2} (Figure 4.4).

Soybean seed yield at Carman 2015 and Scott 2015 was combined across seeding dates because date had no effect at these site-years and there was no rate*date interaction (Table 4.2) . At both site-years, soybean seed yield increased consistently with increasing seeding rates (Figure 4.4). At Carman 2015, seed yield had a linear relationship with seeding rate, and the overall range of yield was much lower compared to the Scott site. Yield ranged from 673 to 1035 kg ha^{-1} as density increased from 10 plants m^{-2} to 160 plants m^{-2}, whereas seed yield ranged from 186 to 1422 kg ha^{-1} at Scott (Figure 4.4).

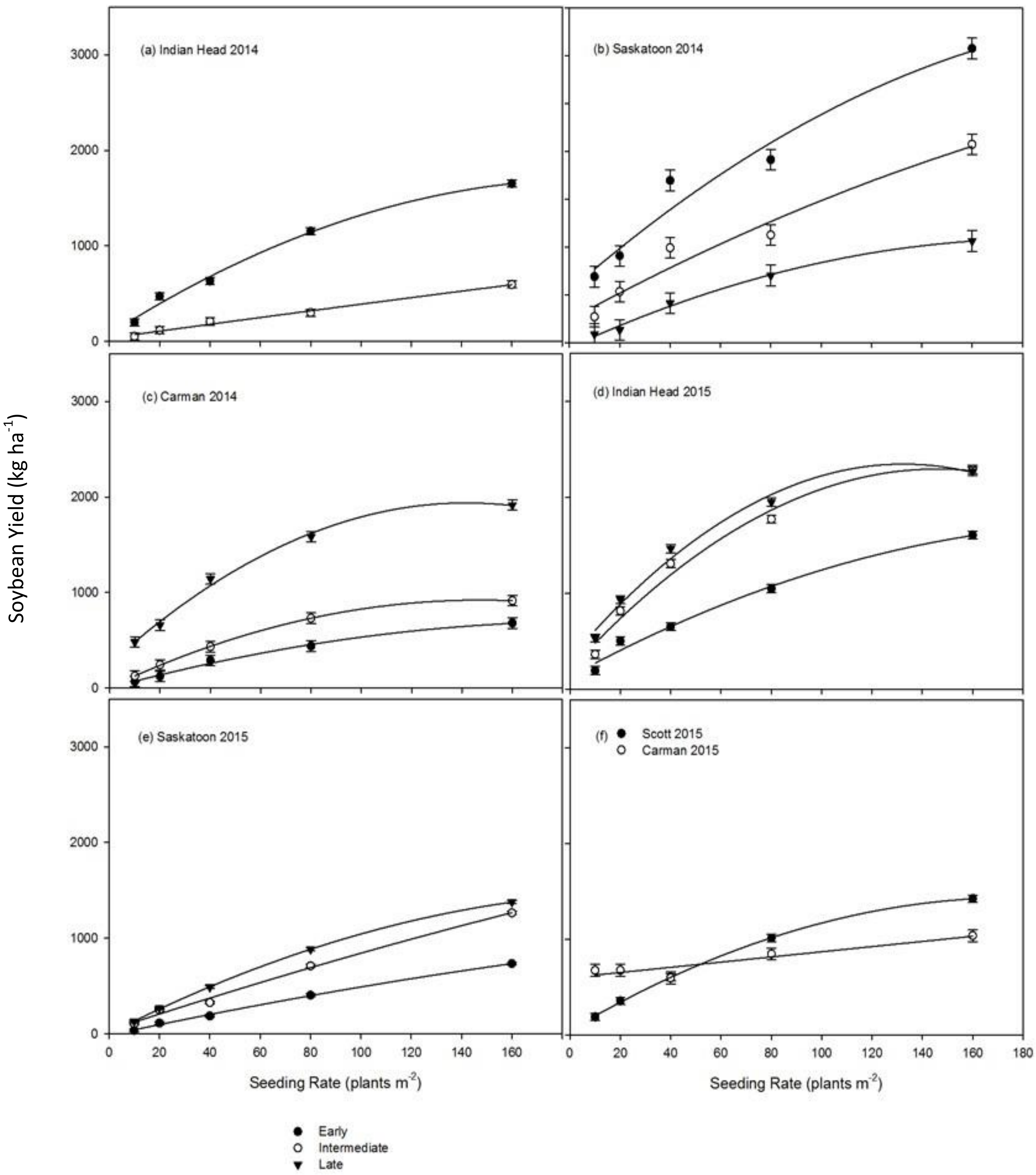

Figure 4.4. Effect of seeding rate and seeding date on soybean yield at site years where there were site*date*rate interactions (a-e); and Carman 2015 and Scott 2015, where there were no site*date*rate interactions (f). Bars indicate +/-1 SEM. **Line equations for seeding dates: (a)** Early: $y = -0.0434x^2 + 16.794x + 76.618$. $R^2 = 0.9928$. Intermediate: $y = -0.001x^2 + 3.6416x +$

35.209. $R^2 = 0.9901$. **(b)** Early: $y = -0.0461x^2 + 23.054x + 541.87$. $R^2 = 0.9616$. Intermediate: $y = -0.0188x^2 + 14.358x + 237.1$. $R^2 = 0.9605$. Late: $y = -0.0322x^2 + 12.107x - 52.423$. $R^2 = 0.9944$. **(c)** Early: $y = -0.0182x^2 + 7.1369x + 0.8078$. $R^2 = 0.994$. Intermediate: $y = -0.0422x^2 + 12.421x + 6.5059$. $R^2 = 0.9999$. Late: $y = -0.0839x^2 + 23.785x + 253.42$. $R^2 = 0.9947$. **(d)** Early: $y = -0.032x^2 + 14.315x + 131.45$. $R^2 = 0.9864$. Intermediate: $y = -0.098x^2 + 28.647x + 203.9$. $R^2 = 0.9816$. Late: $y = -0.1155x^2 + 30.608x + 320.99$. $R^2 = 0.9872$. **(e)** Early: $y = -0.006x^2 + 5.6412x - 14.268$. $R^2 = 0.9984$. Intermediate: $y = -0.0064x^2 + 8.7189x + 34.508$. $R^2 = 0.9945$. Late: $y = -0.0303x^2 + 13.441x + 1.7394$. $R^2 = 0.9998$. **(f)** Scott 2015: $y = -0.0438x^2 + 15.612x + 45.428$. $R^2 = 0.9997$. Carman 2015: $y = 2.7054x + 596.86$. $R^2 = 0.8698$.

Soybean TSW

The main effects of rate and date were not significant (p=0.09) for soybean TSW (Table 4.2). There was an overall site*date*rate interaction for TSW, due to three site-years (Carman 2014, Indian Head 2014, and Scott 2015) having a rate*date interaction. However, there were no clear and consistent trends between these three site-years and TSW differences were very small between seeding rates and dates. The results were of little biological significance and therefore, they are not presented.

4.3.2 Seeding Rate and Seeding Date Effects on Volunteer Canola

Volunteer Canola Shoot Biomass

Seeding rate had a significant effect on volunteer canola shoot biomass (P<0.0001) and there was also a significant site*date interaction for canola biomass (Table 4.2). However, there was no seeding date effect when site-years were combined. It is likely that there was a site*date interaction because two of the seven site-years (Indian Head 2014 and Saskatoon 2014) exhibited a seeding date effect, while the remaining five had no statistically significant date effect (Table 4.2). At Indian Head 2014 and Saskatoon 2014, where date was statistically significant, volunteer canola shoot biomass was lowest at the early seeding date (data not shown). Canola shoot biomass at the five sites where date was not significant also tended to be lowest at the early seeding date (data not shown). Hence, since the trend was consistent across all site-years, site-years and seeding dates were combined.

A significant site*rate interaction also existed for volunteer canola shoot biomass (Table 4.2). At site-years where canola biomass was <1500 kg ha^{-1} (Carman 2014, Indian Head 2014 and Carman 2015), increasing seeding rate had a smaller effect on shoot biomass due to the magnitude of the decline in volunteer canola shoot biomass being lower. This led to an overall site*rate interaction, as the response to seeding rate differed within site-years as a function of the amount of volunteer canola present at each site. In contrast, the remaining four site-years with volunteer canola biomass above 1500 kg ha^{-1} had much steeper declines in volunteer canola shoot biomass as seeding rates increased (Figure 4.5).

At all site-years, a consistent trend existed wherein volunteer canola shoot biomass tended to decrease with increasing seeding rate. When seeding rate was increased from 40 plants m^{-2} to 80 plants m^{-2}, the decrease in volunteer canola biomass ranged from 17% to 45% across site-years, with the exception of Scott 2015, which increased 6% (Figure 4.5). When seeding rate was increased from 80 plants m^{-2} to 160 plants m^{-2}, the decrease in volunteer canola biomass ranged from 6% to 62% (Figure 4.5).

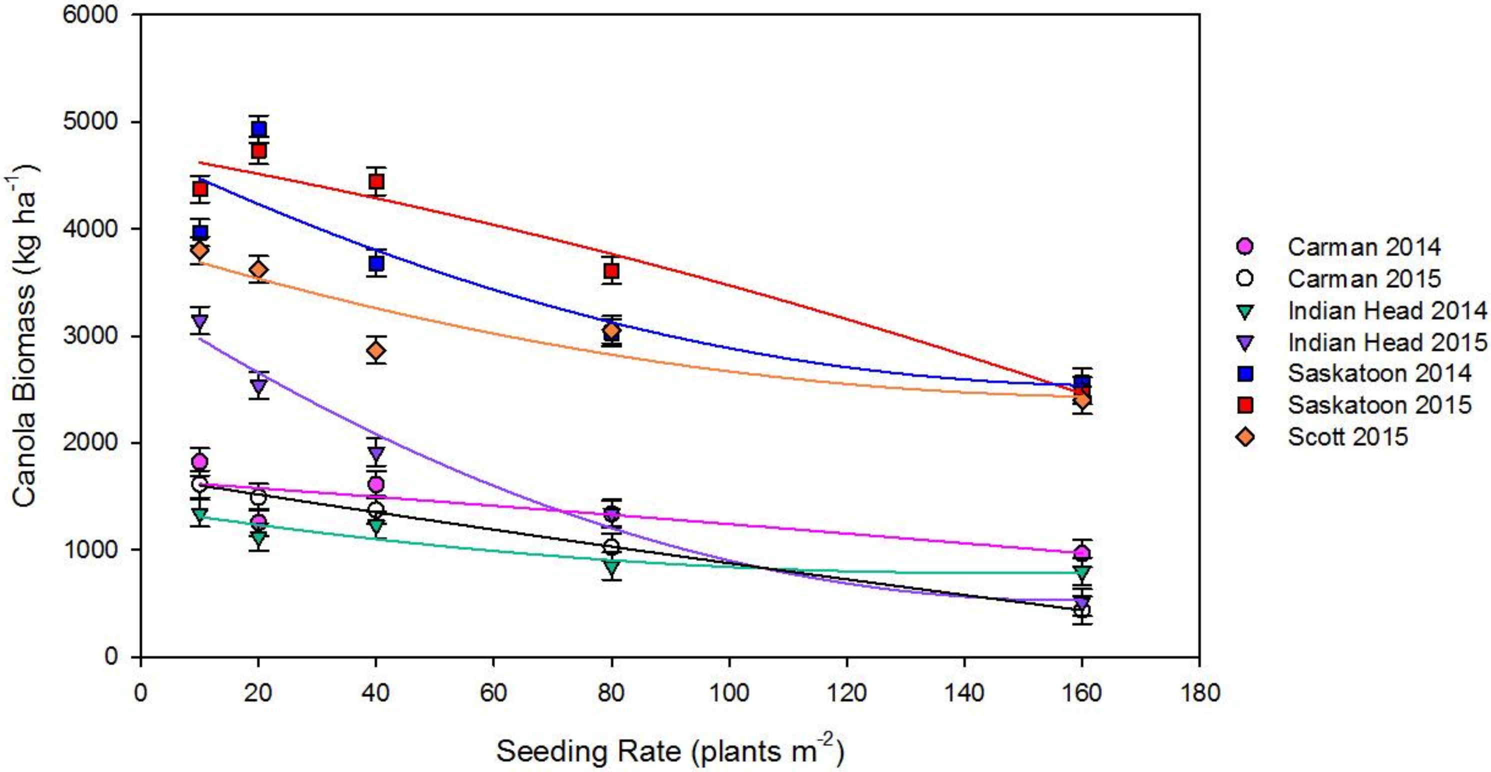

Figure 4.5. Volunteer canola shoot biomass response to seeding rate across all seven site-years. Bars indicate +/-1 SEM. Line equations: **Carman 2014**: $y = -0.0024x^2 - 3.8977x + 1656.8$ $R^2 = 0.6356$. **Carman 2015**: $y = 0.005x^2 - 8.6171x + 1689.3$. $R^2 = 0.9985$. **Indian Head 2014**: $y = 0.0293x^2 - 8.4452x + 1392.7$. $R^2 = 0.8503$. **Indian Head 2015**: $y = 0.1125x^2 - 35.422x + 3319.2$. $R^2 = 0.9783$. **Saskatoon 2014**: $y = 0.0789x^2 - 26.284x + 4727.2$. $R^2 = 0.7678$. **Saskatoon 2015**: $y = -0.0276x^2 - 9.698x + 4720.6$. $R^2 = 0.952$. **Scott 2015**: $y = 0.0495x^2 - 16.785x + 3852.8$. $R^2 = 0.8231$.

Volunteer Canola Seed Contamination

Volunteer canola seed contamination data was not collected at Indian Head in 2014 or 2015 and thus, these sites were excluded from the analysis. Seeding rate had a significant effect on volunteer canola seed contamination (P=0.0012) (Table 4.2), and the trend was similar to that observed for volunteer canola shoot biomass (Figure 4.6). Volunteer canola seed contamination decreased linearly with increasing seeding rates, largely due to greater soybean crop competition at higher crop densities. Volunteer canola seed contamination was highest at lower seeding rates due to poor crop competition.

Volunteer canola seed contamination also exhibited a site*rate interaction due to differences in the magnitude of response to seeding rate, similar to volunteer canola shoot biomass. This interaction tended to be a function of the amount of volunteer canola present at each site-year (Figure 4.6). For example, when seeding rate was increased from 40 plants m^{-2} to 80 plants m^{-2}, the decrease in volunteer canola seed contamination ranged from 9% to 34% across all site-years (Figure 4.6). When seeding rate was increased from 80 plants m^{-2} to 160 plants m^{-2}, the decrease in canola seed contamination ranged from 21% to 56% across all site-years (Figure 4.6).

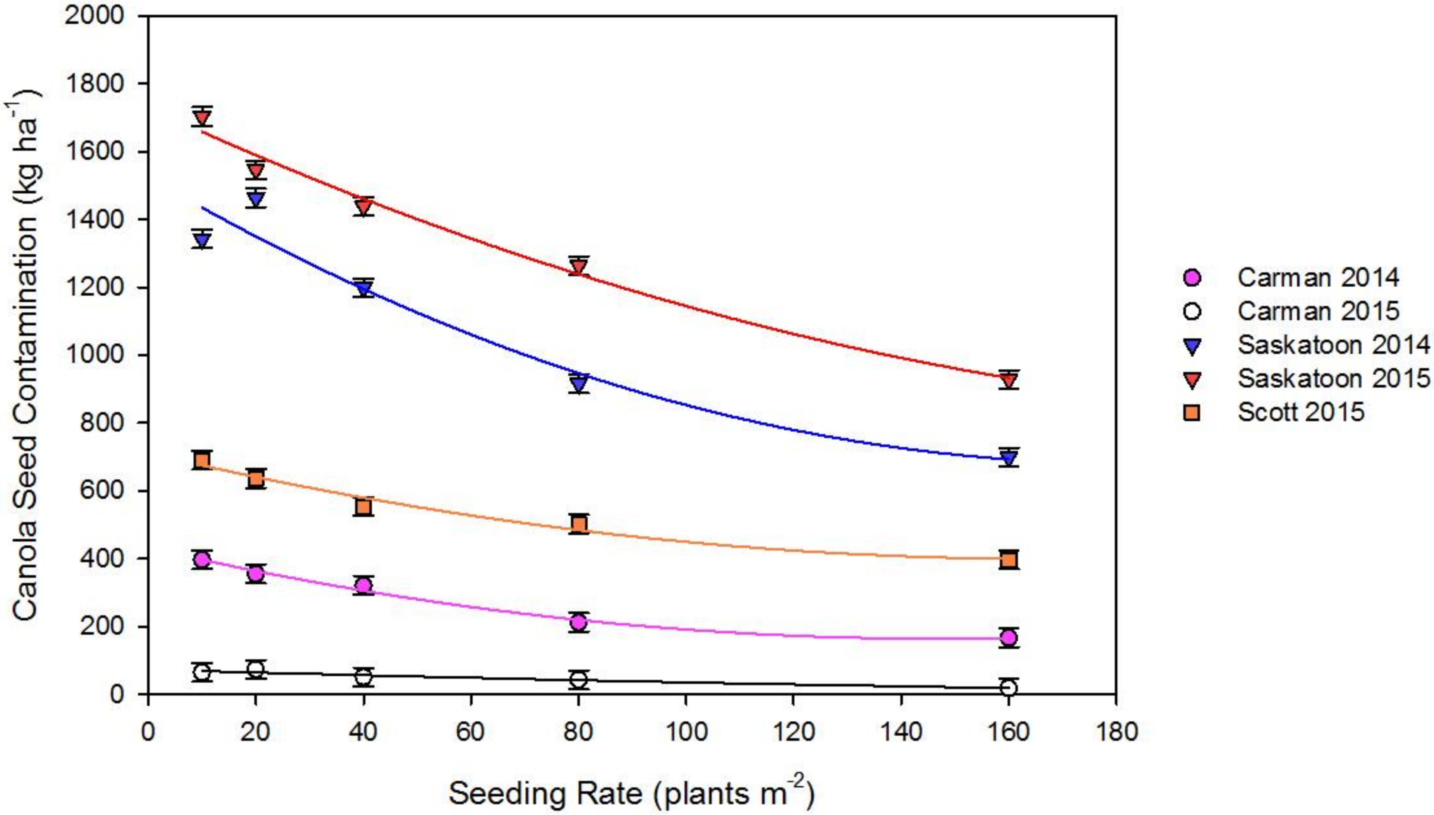

Figure 4.6. Volunteer canola contamination response to seeding rate at five all site-years. Bars indicate +/-1 SEM. Line equations: **Carman 2014**: $y = 0.0124x^2 - 3.6442x + 431.67$. $R^2 = 0.9903$. **Carman 2015:** $y = 0.0007x^2 - 0.4482x + 73.264$. $R^2 = 0.9253$. **Saskatoon 2014**: $y = 0.0253x^2 - 9.2581x + 1525.3$. $R^2 = 0.9429$. **Saskatoon 2015**: $y = 0.0145x^2 - 7.3056x + 1730.3$. $R^2 = 0.9857$. **Scott 2015**: $y = 0.0111x^2 - 3.7214x + 710.71$. $R^2 = 0.9756$.

4.4 Economic Analysis

Maximum soybean yield was not reached at any seeding rate in most site-years; therefore an economic analysis was conducted to determine both the optimal seeding rate for growers and the economic benefit of different seeding rates.

Soybean seed yield and dockage predictions were computed for all seeding rates using the quadratic formula:

$$Y = ax^2 + bx + c$$

where *a* is the quadratic coefficient, *b* is the linear coefficient, *c* is the y intercept, and *x* is the seeding rate. Prediction values used are from combined analysis of each variable. Coefficient values for parameters *a*, *b*, and *c* to predict seed yield are as follows:

a = -0.034

b = 13.277

c = 189.81

Coefficient values for parameters *a*, *b*, and *c* to predict dockage are as follows:

a = 0.00213

b = -0.6335

c = 73.67

Volunteer canola shoot biomass predictions for all seeding rates were calculated using the linear response formula:

$$Y = ax^2 + b$$

where a is the linear coefficient and b is the y intercept.

Coefficient values for parameters a and b to predict canola shoot biomass are as follows:

$$a = -15.95$$

$$b = 3134.18$$

Predicted yields for seeding rates used in the experiment, as well as seeding rates that were not used in the experiment, are shown in Table 4.4.

Table 4.4. Predicted soybean yields at various seeding rates between 10 and 160 plants m^{-2}.

Seeding Rate (plants m^{-2})	Soybean Yield (kg ha^{-1})
10	341
20	473
40	713
50	822
60	924
70	1019
80	1106
90	1186
100	1259
160	1542

The highest contribution margin was observed at a seeding rate of 10 plants m^{-2} at \$90.37 per hectare, and it becomes negative at seeding rates higher than 80 plants m^{-2} due to high seed costs (Table 4.5). Net income consistently decreases with increasing seeding rates, as yield increases are not high enough to offset the increased seed cost. As seeding rate increases, the decline in contribution margin (net income) becomes larger. For example, the difference in contribution margin between 10 and 20 plants m^{-2} is only -\$1.22, while the difference between

40 and 50 plants m^{-2} is -$10.75. Seeding rate significantly impacts soybean yield and volunteer canola biomass, as increasing the seeding rate from 40 plants m^{-2} to 50 or 60 plants m^{-2} increases soybean yield 15-30% and decreases canola biomass 14-23%.

Table 4.5. Soybean seed cost, market price, and predicted yield, predicted volunteer canola biomass and dockage, gross income and contribution margin for all seeding rates.

Seeding Rate (plants m^{-2})	Seed Cost ($/ha)	Market Price ($/kg)	Soybean Yield (kg ha^{-1})	Canola Biomass (kg ha^{-1})	Soybean Yield Difference (%)	Canola Biomass Difference (%)	Dockage (%)	Gross Income ($/ha)	Contribution Margin ($/ha)
10	58.29	0.44	341	3182	-52.2	19.18	72.36	148.66	90.37
20	116.58	0.44	473	3012	-33.66	12.81	66.26	205.74	89.15
40	233.17	0.44	713	2670	0	0	55.44	310.36	77.19
50	291.46	0.44	822	2337	15.29	-14.25	47.40	357.90	66.44
60	349.75	0.44	924	2177	29.59	-22.65	43.40	402.31	52.56
70	408.04	0.44	1019	2018	42.91	-32.31	39.83	443.67	35.63
80	466.34	0.44	1106	1988	55.12	-34.3	39.24	481.50	15.17
90	524.63	0.44	1186	1699	66.34	-57.15	33.96	516.38	-8.24
100	582.92	0.44	1259	1539	76.58	-73.49	31.67	548.17	-34.75
160	932.67	0.44	1542	623	116.27	-328.57	28.70	671.35	-261.32

Soybean seed yield and dockage predictions were calculated using the quadratic formula: $Y = ax^2 + bx + c$
Canola shoot biomass predictions were calculated using the linear response formula: $Y = ax^2 + b$
Difference in soybean yield and canola shoot biomass was determined by comparing each seeding rate to the standard rate of 40 plants m^{-2}
Gross income was calculated by multiplying soybean seed yield by market price
Contribution margin was calculated by subtracting the seed cost from the gross income

4.5 Discussion

This study demonstrated that cultural weed control methods, such as altering soybean seeding rate and seeding date, can substantially impact soybean yield and reduce competition from volunteer canola. The effects of seeding date on soybean development were inconsistent and differed among site-years, likely due to a combination of factors. The early seeding date had the greatest soybean emergence, shoot biomass and seed yield at Indian Head 2014 and Saskatoon 2014. These two site-years were also the only two in which seeding date affected volunteer canola biomass, with the early seeding date having the lowest canola shoot biomass. This indicates that early planted seeds were able to effectively compete with volunteer canola and is similar to the findings of Klingaman and Oliver (1994), who reported that soybean yield loss due to weed interference increased as planting date was delayed from early May to early June. In our experiment, the early seeding date matured earlier and may have reduced yield losses due to frost damage. Several studies have reported higher soybean yields with early planting (Parvez et al. 1989; Hardman and Gonsolus, 1994; Kane et al. 1997; De Bruin and Pederson, 2008b; Robinson et al. 2009). However, some of these studies used seeding dates that are either too early or too late for western Canada.

The latest seeding date yielded highest at Carman 2014, Indian Head 2015 and Saskatoon 2015, and soybean emergence was greatest at many of these sites as well. This contrasts with results at the two Saskatchewan sites in 2014, but other studies have also reported that yields of later seeded soybean were higher than early seeded soybean (Buhler and Gunsolus, 1996; Rushing and Oliver, 1998). The authors suggested this was often due to inadequate rainfall early in the season and decreased weed competition with later planting.

Although seeding date effects on soybean differed among site-years, seeding rate effects were very consistent. Increasing seeding rate resulted in higher soybean emergence, plant height, shoot biomass and seed yield. Increasing soybean seeding rate also positively influenced its competitive ability with weeds. Volunteer canola shoot biomass and seed contamination consistently decreased at higher seeding rates. Several studies have also reported lower weed densities and biomass when soybean is seeded at high densities (McWhorter and Barrentine, 1975; Nice et al. 2001; Norsworthy and Oliver, 2001; Guillermo et al. 2009). Crops seeded at a higher population density tend to have a competitive advantage over weeds, due to rapid canopy development and therefore improved competitiveness, as well as increased plant stand (Guillermo et al. 2009; Place et al. 2009). Soybean seeded at lower seeding rates experienced more weed competition due to higher densities of volunteer canola, and therefore crop growth was likely more stunted. Soybean seeded at low seeding rates probably also exhibited shade avoidance mechanisms in response to dense volunteer canola stand which affected growth and yield. Shade avoidance is triggered by a reduction in red: far red light in dense environments and has been shown to increase internode elongation, reduce branching, and decrease plant yield in soybean (Green-Tracewicz et al. 2011).

Soybean shoot biomass and seed yield consistently increased with increasing seeding rates, but the incremental response tended to decrease with increasing seeding rates. This is likely due to the law of constant final yield, where total standing plant biomass initially increases in proportion to density, levels off, and then remains constant as density increases further (Weiner and Freckleton, 2010). However, in most cases, maximum yield was not achieved at the densities tested in this experiment, and we did not achieve constant final yield. Plant densities required to achieve maximum yield, calculated by differentiating the quadratic formula, ranged from 142-250 plants m^{-2}. Several studies have also found that increasing soybean seeding rate increased yield (Elmore, 1998; Place et al. 2009; Cox and Cherney, 2011). Studies have also found that increasing seeding rate in other pulse crops, such as field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* L.), results in higher yield and lower weed biomass in organic production systems on the prairies (Baird et al. 2009a; Baird et al. 2009b).

The effect of seeding rate appeared to differ at different seeding dates in some site-years. The inconsistent effects of seeding date on soybean shoot biomass and seed yield that we observed were probably due, at least in part, to variable environmental conditions that affected soybean emergence. For example, the early seeding date yielded highest at Saskatoon 2014, where precipitation was 167% and 149% of the long-term normal in May and June, while July and August precipitation was only 83% and 42% of the long-term normal, respectively. Percent emergence of soybean was also highest at the early seeding date at Saskatoon 2014. The above-normal precipitation in May and June may have allowed for better soybean establishment and early season growth. Conversely, at Saskatoon in 2015, May and June precipitation was 17% and 32% of the long-term normal, respectively, while July and August received 158% and 131% of the long-term normal precipitation. Indian Head exhibited the same trend in 2015. Percent emergence was also highest at the late seeding date at Indian Head 2015. A very dry spring followed by a wetter than normal summer may account for why the late seeding date yielded highest at Saskatoon 2015 and Indian Head 2015, as lack of moisture may have inhibited establishment and germination at the early seeding date. Buhler and Gonsolus (1996) also noted higher soybean yields with delayed planting and attributed this to early season moisture stress that reduced yield of early planted soybean. Soybean emergence is reduced when initial soil water content is inadequate, and the reduction in emergence depends on the length of time until adequate water content is restored (Helms et al. 1996).

Ultimately, the responses to seeding dates observed in this study are probably more dependent on the timing of volunteer canola emergence rather than seeding date itself. In this experiment, the timing of volunteer canola emergence was consistent with each seeding date, as canola was seeded immediately after soybean at each seeding date. This is consistent with research by Eaton et al. (1976) that found that weed species were most competitive when soybean and weeds were established simultaneously, and weeds seeded at the same time as soybean or 10 days later significantly reduced soybean yield. Volunteer canola emerges early in spring and requires minimal GDD for emergence (90 and 132 GDD, Lawson et al. 2006). They also found that germination of volunteer canola prior to seeding was much lower with cool spring temperatures and low moisture levels. In our study, seeding date effects were dependent on environmental conditions such as soil moisture and temperature. In most site-years, seeding date generally did not significantly impact volunteer canola biomass or seed contamination. Considering that volunteer canola generally emerges early, it is likely that seeding date effects are dependent on how this variable impacts soybean competitiveness, as well as its direct effect on volunteer canola.

Although seeding date treatments tended to show inconsistent effects that depended on conditions at each site-year, soybean seed yields tended to be greatest when planted after May 22nd and before June 11th, indicating an optimal planting date range for soybean in western Canada. However, planting around June 11th may be too late for this short growing season in some years due to fall frost. The long-term average date for the first frost in Saskatchewan sites is September 9th-15th, and the first frost generally occurs from September 11th-16th at Carman

(Saskatchewan Crop Insurance Corporation; Manitoba Agriculture). Volunteer canola would also be well-established by June 11th, which may present a disadvantage to soybean if it is not well-managed prior to planting, through the use of a pre-emergent herbicide or mechanical weed control. Therefore, the optimal planting date range is from May 22nd to around June 1st in western Canada.

Maximum soybean yield was not reached at most of the site-years, and it is very likely that high seeding rates may not be economically feasible for growers. Based on the economic analysis performed, the grower's contribution margin will be negative when seeding rates exceed 80 plants m^{-2}, due to high seed costs (Table 4.5). The highest net income is reached at 10 plants m^{-2}, which is one quarter of the current recommended seeding rate. However, this seeding rate produced very high volunteer canola shoot biomass and contamination. Therefore, 10 plants m^{-2} is not an optimal seeding rate, as there may be price deductions due to very high dockage numbers, which would decrease the selling price for the grower. However, another important consideration is the contribution to the seed bank. Low soybean seeding rates result in higher densities of volunteer canola present. If volunteer canola is not controlled, it will set seed and replenish the seed bank for the following years, as volunteer canola can produce up to 3,600 seeds m^{-2} (Gulden et al. 2003b) and can persist in soil for several years. This adds an additional cost, as it will require control in the following years and continue to compete with sequential crops for several years.

Given the above, it appears that during years with low or average market prices for soybean, 40 plants m^{-2} is likely the best option for growers, as seeding rates below 40 plants m^{-2} have very high volunteer canola contamination, but contribution margin continues to decrease at seeding rates above 40 plants m^{-2}. However, when market prices are high, growers will see a benefit to increasing the seeding rate to 50-60 plants m^{-2}, as this will potentially increase soybean yield by 15-30% and offset seed costs while minimizing volunteer canola competition. Seeding rates above 70 plants m^{-2} are generally not economic for growers, as the yield benefits are not great enough to offset the high seed costs.

4.6 Conclusion

Seeding date effects were inconsistent across site-years and seeding date effect is dependent on environmental conditions such as precipitation and soil temperature, as well as time of volunteer canola emergence. Results indicate that earlier seeding may improve the crop's competitiveness with volunteer canola, but soil temperature may not be high enough (10°C) for optimum emergence of soybean in some years. Late seeding may be advantageous for the soybean crop, but may reduce its ability to compete with early emerging volunteer canola. Based on seeding date results, the optimal planting date range for soybean in western Canada is May 22nd to June 1st. Higher seeding rates resulted in higher soybean biomass and yield and lower volunteer canola biomass and seed contamination. Based on the economic analysis, the optimal seeding rate is 40 plants m^{-2} in years with low or average market prices. When market prices are high, increasing the seeding rate to 50-60 plants m^{-2} will increase soybean yield significantly, decrease volunteer canola competition and dockage, and increase net income for the grower. Improving crop competition with higher seeding rates will also decrease the contribution of canola seed to the seedbank and therefore, decrease volunteer canola populations in sequential crops.

5.0 General Discussion

The overall objective of this thesis was to determine the best herbicides, seeding rate and planting date to manage volunteer GR canola in GR soybean crops. Differences in soybean productivity, as well as density of volunteer canola, were observed in both experiments in this thesis. Thus, the research demonstrated that soybean's ability to compete with volunteer canola can be significantly improved through both chemical and cultural management techniques. Increasing soybean seeding rate consistently improved the competitive ability of soybean, while seeding date results were variable. Several herbicide options exist for controlling volunteer GR canola in GR soybean, however the optimal herbicide combinations depend on economics and agronomics.

5.1 Chemical control of volunteer GR canola in GR soybean

It was hypothesized that saflufenacil pre-emergence, followed by imazamox+bentazon post-emergence, would result in the best control of volunteer canola and high soybean yield with minimal crop injury. The results of Experiment 1 were much broader, however, as many good options were observed for control of volunteer canola. Tribenuron+bentazon, tribenuron+imazamox+bentazon, tribenuron+cloransulam-methyl, saflufenacil+bentazon, saflufenacil+imazamox+bentazon and saflufenacil+cloransulam-methyl all provided good control with minimal crop injury. 2,4-D pre-emergence and thifensulfuron and fomesafen post-emergence all caused unacceptable crop injury and therefore are not suitable products.

Although many of the herbicide combinations used are suitable, producers need to consider other weed species when making their herbicide decisions. For example, weed species that have developed resistance to both Group 9 (glyphosate) and Group 2 herbicides will not be controlled in-crop by post-emergence applications of cloransulam-methyl and glyphosate, regardless of pre-emergence herbicide. Kochia (*Kochia scoparia* (L.) Schrad.) resistant to both Group 2 and 9 has been reported in the prairies (Beckie et al. 2015). Moreover, wild oat (*Avena fatua* (L.)), green foxtail (*Setaria viridis* (L.)) and cleavers (*Galium aparine* (L.)) are predicted to be the next weed species to develop glyphosate resistance (Beckie, 2011). Resistance to Group 2 herbicides has already been reported in all three of these weed species on the prairies (Heap, 2017). In our study, several of the herbicides used were Group 2 herbicides (tribenuron, thifensulfuron, cloransulam-methyl).

By contrast, there are options from other groups. Bentazon is a Group 6 herbicide; currently there are no reported cases of Group 6 resistant weeds in western Canada. Additionally, saflufenacil is a Group 14 herbicide. Currently, the only reported case of Group 14 resistance is in wild oat in Manitoba in 2015, a weed that has fairly high inherent tolerance to most Group 14 herbicides (Heap, 2017). Evans et al. (2016) found that mixing herbicide groups was strongly linked to reducing selection for glyphosate resistance in weeds, and mixing three or more modes of action annually resulted in delayed herbicide resistance. Fields receiving herbicide mixes containing three modes of action were also 51 times less likely to have glyphosate-resistant weeds than fields with only two modes of action used. The only herbicide combinations in our experiment that contained at least three modes of action were treatments in which glyphosate was tank-mixed with a post-emergence application of imazamox+bentazon (Group 2+6). Including saflufenacil as a pre-emergence herbicide with this combination would mean four different modes of action applied in a single year, which is beneficial for resistance management.

Taking herbicide resistance into consideration, optimal herbicide combinations for management of volunteer GR canola in GR soybean are glyphosate combined with tribenuron+bentazon, tribenuron+imazamox+bentazon, saflufenacil+bentazon, and saflufenacil+imazamox+ bentazon. Tribenuron+imazamox+bentazon and saflufenacil+imazamox+ bentazon are the optimal choices because they contain at least three modes of action; and therefore, will be the most effective at delaying glyphosate resistance development in weeds. Tribenuron+cloransulam-methyl provided good control of volunteer canola and was cost-effective; however both the pre and post-emergence herbicide applications would contain only Group 2 and Group 9 and would be less effective in delaying glyphosate resistance evolution. Saflufenacil + cloransulam-methyl would include a Group 14 pre-emergence, but also would only contain Group 2 and Group 9 herbicides post-emergence. Therefore, tribenuron+imazamox+bentazon and saflufenacil+imazamox+ bentazon are the best herbicide combinations for managing volunteer GR canola in GR soybean.

5.2 Cultural control of volunteer GR canola in GR soybean

It was hypothesized that soybean competition with volunteer canola would be significantly improved with higher seeding rates and a mid-May seeding date. The hypothesis was partially confirmed, as 160 plants m^{-2} consistently resulted in the highest soybean shoot biomass and seed yield, and lowest volunteer canola shoot biomass across site-years. However, seeding date effects were inconsistent and differed with site-year. Based on the economic analysis, 40 plants m^{-2} was the optimal seeding rate in years with below or average market prices, and 50-60 plants m^{-2} was optimal when market prices are high. The optimal range in optimal seeding dates for soybean in western Canada was found to be between May 22nd and June 1st.

Optimal seeding rate and seeding date are components of an integrated weed management system (IWM). IWM focuses on the integration of methods rather than reliance on a single method for weed management (Swanton et al. 2008). IWM is essential for delaying herbicide resistance in weeds because it reduces the reliance on herbicides alone. One important component of IWM is enhancement of crop competitiveness, often done by altering planting patterns (Swanton and Weise, 1991). Establishing a crop with a more uniform and dense canopy by increasing seeding rates increases its ability to suppress weeds (Blackshaw et al. 2008). Enhancing the competitiveness of the crop through increasing the seeding rate can also considerably improve herbicide activity (O'Donovan et al. 2007). Studies have found that higher crop seeding rates in competitive crops such as wheat, barley and canola can compensate for reduced herbicide rates without reducing weed control (O'Donovan et al. 2001; Beckie and Kirkland, 2003; O'Donovan et al. 2004). Conversely, higher seeding rate did not compensate for reduced herbicide rates in field pea, which similar to soybean, has lower competitive ability (Beckie and Kirkland, 2003). However, increased seeding rates combined with full herbicide rates in soybean may provide improved weed control. Therefore, chemical and cultural weed management techniques complement each other, and using both methods improves the efficacy and benefit of both. Although herbicides and altering seeding rate alone do not constitute an IWM system, combining chemical and cultural methods reduces the reliance on herbicides alone and reduces selection pressure for herbicide resistance in weeds. By seeding in the optimal range of May 22nd to June 1st and using a soybean seeding rate of 40-60 plants m^{-2} combined with applications of tribenuron or saflufenacil pre-emergence and imazamox+bentazon post-emergence, growers can maximize soybean competitiveness with volunteer canola, delay herbicide resistance and maximize soybean yield while still being economically feasible.

Another important component of IWM is seed bank dynamics (Swanton and Weise, 1991). As mentioned previously, volunteer canola can produce large additions to the seed bank and canola seed can remain viable in soil for several years (Legere et al. 2001; Gulden et al. 2003a). Because our experiment included no chemical control, volunteer canola densities were still relatively high at harvest timing, even at high seeding rates. Therefore, the contribution of volunteer canola seed to the seed bank was very high (up to 1700 kg ha^{-1} at the lowest seeding rate), though crop competition has a significant impact on weed seed production. For example, competition from soybean reduced common cocklebur and velvetleaf seed production 84% and 82% respectively, compared to no crop competition (Senseman and Oliver 1993; Lindquist et al. 1995). Similarly, in our experiment, increasing the soybean seeding rate from 40 plants m^{-2} to 80 plants m^{-2} decreased canola seed contamination by 9% to 34% at all site-years; increasing seeding rate from 80 plants m^{-2} to 160 plants m^{-2} decreased canola seed contamination by 21% to 56%. Therefore, improved crop competition can significantly reduce inputs to the seed bank and reduce volunteer canola populations in soybean crops, particularly when used in addition to chemical control methods.

5.3 Management Implications

Germination of weed seeds such as volunteer canola depends heavily on environmental conditions in the spring. In years where spring conditions are not conducive to early weed emergence, the majority of volunteer canola likely will not have emerged by the time of the pre-emergence herbicide application. Therefore, post-emergence herbicide application is critical to control the majority of volunteer canola that has emerged following the pre-emergence application, as well as controlling multiple flushes of volunteer canola throughout the growing season. When GR volunteer canola is present in GR soybean crops, applying both a pre-emergence and post-emergence herbicide is critical. This will likely result in a higher herbicide cost for growers, but pre-emergence applications alone will likely not sufficiently control volunteer canola. Moreover, densities may be too high by the time the post-emergence herbicide is applied to rely only on post-emergence applications.

Increasing soybean seeding rate to 50-60 plants m^{-2} when volunteer canola is present would result in a higher seed cost for growers, but a potential yield benefit of 15-30% could be realized. It could also improve the competitiveness of the crop with volunteer canola and reduce reliance on herbicides alone, while reducing canola biomass by approximately 14-23%. This in turn would reduce the contribution to the seed bank, which would require control in the following years. To seed soybean in the optimal seeding date range, growers may have to delay seeding of soybean until May 22nd and up until June 1st, which may be later than usual in some cases.

It is critical for growers to use more than one method of weed control, and not rely singularly on herbicides. Several other cultural weed management techniques have been found to be effective at improving the competitiveness of soybean with weeds. These techniques have the potential to be combined with the results of this thesis for an IWM system for soybean in western Canada. Studies have found that narrow row spacing (19-38 cm) increases soybean yield and decreases weed biomass and resurgence, mainly due to rapid canopy formation and increased light interception (Wax and Pendleton, 1968; Yelverton and Coble, 1991; Hock et al. 2006; De Bruin and Pederson, 2008a). Mechanical weed control methods such as inter-row cultivation and rotary hoeing can also be integrated into a weed management system for soybean, however there is potential for crop injury. Rotary hoeing is effective on weeds that have germinated but not yet emerged, although it is not effective on weeds that germinate from deeper than 5 cm, while inter-row cultivation is most effective on emerged weeds that are 10 to 15 cm tall (Gunsolus, 1990). By combining both chemical methods such as mixing herbicide groups and cultural control methods to improve crop competitiveness, growers can effectively manage GR volunteer canola in GR soybean in a sustainable manner.

5.4 Future Research

Only one soybean cultivar was used in both studies, and it is possible that there are varietal differences in sensitivity to different herbicides. For example, the saflufenacil label specifies that some varieties may be more sensitive to the herbicide and injury may occur (Saskatchewan Ministry of Agriculture, 2016). The cultivar used in this study is also very early maturing, but relatively low yielding. Therefore, research using current commonly grown cultivars should be conducted to evaluate consistency of crop tolerance.

Research should also be conducted to evaluate the effect of 2,4-D on crop injury and efficacy on volunteer canola using different planting intervals. Injury was observed with the recommended interval of 7 days between application and crop planting, and therefore research should include longer planting intervals, such as 10, 14 and up to 21 days. This would determine whether 2,4-D is a suitable product for soybean in western Canada and the required planting interval to avoid crop injury. Trials should be conducted in variable soil types and environments, as crop injury from 2,4-D tends to depend on environmental conditions, and therefore planting intervals should be evaluated under different growing conditions and soil characteristics.

The results of Ch.4 narrowed the optimal seeding date for soybean in western Canada to between May 22nd and June 1st. However, the soybean cultivar used in this study, P001T34R, is a very early maturing cultivar with a corn heat unit (CHU) requirement of 2300. It is possible that this cultivar may have been less affected by late planting due to its shorter maturity requirement. Other cultivars with higher CHU requirements may be more negatively affected by late planting, if frost occurs before the crop can reach physiological maturity. It should be noted that while P001T34R is early maturing, it tends to be lower yielding than many other cultivars available in western Canada (Saskatchewan Seed Guide, 2016). Therefore, future research should focus on this planting date range using higher yielding, more commonly grown cultivars with slightly higher CHU requirements to evaluate whether there are any detrimental effects to planting soybean up until June 1st in western Canada.

Future studies should also focus on integrating chemical and cultural weed management and determining IWM strategies for growing GR soybean in western Canada. The studies presented in this thesis were separate studies and therefore not true IWM studies. Future research should focus on combining the use of herbicides, seeding rates and seeding dates, as well as mechanical weed control and row spacing in soybean. By integrating all of these components, an IWM system can be developed for management of volunteer GR canola in GR soybean in western Canada.

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Appendix 1

Table A1. Means comparison of treatment efficacy ratings at 7-10, 21-28 and 56 DAT for given treatments.

Pre-emergent Herbicide	Post-emergent Herbicide	7-10 DAT	21-28 DAT	56 DAT
Glyphosate	NONE	0 D	0 D	0 E
2,4-D	Bentazon	83.0 ABC	82.1 BC	80.6 ABC
2,4-D	Fomesafen	92.5AB	81.1 BC	75.3 ABCD
2,4-D	Imazamox+bentazon	87.7 ABC	92.2 AB	87.5 A
2,4-D	Thifensulfuron	81.0 BC	80.3 C	72.3 BCD
2,4-D	Cloransulam-methyl	82.3 BC	94.8 A	78.5ABCD
Tribenuron	Bentazon	86.7 ABC	80.1 C	78.6 ABCD
Tribenuron	Fomesafen	95.5 A	85.8 ABC	78.5 ABCD
Tribenuron	Imazamox+bentazon	81.8 BC	88.2 ABC	84.9 AB
Tribenuron	Thifensulfuron	76.9 C	80.3 C	64.6 D
Tribenuron	Cloransulam-methyl	80.4 BC	89.3 ABC	84.1 ABC
Saflufenacil	Bentazon	84.4 ABC	79.1 C	78.2 ABCD
Saflufenacil	Fomesafen	90.9 AB	87.2 ABC	77.4 ABCD
Saflufenacil	Imazamox+bentazon	83.4 ABC	89.0 ABC	83.6 ABC
Saflufenacil	Thifensulfuron	75.7 C	80.1 C	70.2 CD
Saflufenacil	Cloransulam-methyl	75.3 C	83.6 ABC	83.1 ABC

Means within a column followed by the same letter are not significantly different on the basis of $LSD_{0.05}$.

Table A2. Means comparison of treatment phytotoxicity ratings at 7-10 and 21-28 DAT for given treatments.

Pre-emergent Herbicide	Post-emergent Herbicide	7-10 DAT	21-28 DAT
Glyphosate	NONE	0 E	0 C
2,4-D	Bentazon	13.9 CD	10.5 BC
2,4-D	Fomesafen	18.9 BC	10.1 BC
2,4-D	Imazamox+bentazon	10.1 CDE	7.9 BC
2,4-D	Thifensulfuron	29.5 A	22.6 A
2,4-D	Cloransulam-methyl	9.8 CDE	8.4 BC
Tribenuron	Bentazon	8.0 DE	3.4 C
Tribenuron	Fomesafen	14.2 CD	7.3 BC
Tribenuron	Imazamox+bentazon	6.3 DE	3.3 C
Tribenuron	Thifensulfuron	28.6 AB	17.8 AB
Tribenuron	Cloransulam-methyl	5.4 DE	3.4 C
Saflufenacil	Bentazon	8.8 CDE	4.8 C
Saflufenacil	Fomesafen	14.6 CD	5.8 C
Saflufenacil	Imazamox+bentazon	7.1 DE	4.7 C
Saflufenacil	Thifensulfuron	30.1 A	18.7 AB
Saflufenacil	Cloransulam-methyl	6.5 DE	4.9 C

Means within a column followed by the same letter are not significantly different on the basis of $LSD_{0.05}$.

Table A3. Tukey's HSD means comparison of soybean biomass and yield.

Pre-emergent Herbicide	Post-emergent Herbicide	Soybean Biomass (kg ha^{-1})	Soybean Yield (kg ha^{-1})
Glyphosate	NONE	1147 C	623 D
2,4-D	Bentazon	3262 AB	1283 ABC
2,4-D	Fomesafen	3331 AB	1170 ABCD
2,4-D	Imazamox+bentazon	3740 A	1194 ABCD
2,4-D	Thifensulfuron	2251 BC	737 CD
2,4-D	Cloransulam-methyl	3163 AB	1315 ABC
Tribenuron	Bentazon	3735 A	1448 A
Tribenuron	Fomesafen	3699 A	1406 AB
Tribenuron	Imazamox+bentazon	3628 A	1351 ABC
Tribenuron	Thifensulfuron	2474 ABC	826 ABCD
Tribenuron	Cloransulam-methyl	3691 A	1425 AB
Saflufenacil	Bentazon	3277 AB	1323 ABC
Saflufenacil	Fomesafen	3578 AB	1419 AB
Saflufenacil	Imazamox+bentazon	3606 A	1282 ABC
Saflufenacil	Thifensulfuron	2625 AB	796 BCD
Saflufenacil	Cloransulam-methyl	3602 A	1312 ABC

Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

Table A4. Tukey's HSD means comparison of canola biomass and canola seed production.

Pre-emergent Herbicide	Post-emergent Herbicide	Canola Biomass (kg ha^{-1})	Canola Seed Production (%)
Glyphosate	NONE	1548 A	51.2 A
2,4-D	Bentazon	92 AB	8.4 B
2,4-D	Fomesafen	21 B	7.7 B
2,4-D	Imazamox+bentazon	16 B	6.3 B
2,4-D	Thifensulfuron	251 AB	29.8 AB
2,4-D	Cloransulam-methyl	30 B	8.3 B
Tribenuron	Bentazon	35 B	9.5 B
Tribenuron	Fomesafen	107 AB	10.6 B
Tribenuron	Imazamox+bentazon	70 B	6.9 B
Tribenuron	Thifensulfuron	303 AB	25.6 AB
Tribenuron	Cloransulam-methyl	62 B	8.9 B
Saflufenacil	Bentazon	66 B	12.3 B
Saflufenacil	Fomesafen	67 B	10.4 B
Saflufenacil	Imazamox+bentazon	72 B	8.5 B
Saflufenacil	Thifensulfuron	248 AB	30.7AB
Saflufenacil	Cloransulam-methyl	39 B	11.4 B

Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

Table A5. Pearson's correlation coefficients and P-values between efficacy and phytotoxicity ratings and soybean biomass, soybean yield and canola biomass.

		Ef 7-10	Ef 21-28	Ef 56	Phy 7-10	Phy 21-28
Soybean Biomass	Coeffiecent	0.66372	0.67319	0.71557	-0.11889	-0.27421
	P-value	<.0001	<.0001	<.0001	0.0453	<.0001
Soybean Yield	Coeffiecent	0.5342	0.60647	0.69511	-0.2539	-0.47071
	P-value	<.0001	<.0001	<.0001	<.0001	<.0001
Canola Biomass	Coeffiecent	-0.60931	-0.65345	-0.48793	NA	NA
	P-value	<.0001	<.0001	<.0001		